

Car Door Sound Quality Assessment - A Review for NVH Performance Research



Pandurang Maruti Jadhav, Kishor B. Waghulde, Rupesh V. Bhortake

Abstract: Customer comfort in terms of NVH is a tangible and intangible effect. NVH is directly and indirectly connected to the psychoacoustics of human beings and their lives. As part of the advanced NVH analysis, the effects of noise have been studied in terms of psychoacoustic parameters, including loudness, sharpness, roughness, fluctuation strength, and tonality. A car door or door assembly is a crucial component of a car or vehicle. The door is softly and flexibly connected to the main body of the vehicle, protecting passengers from weather effects and accidental impacts. Due to the inherent flexibility of the door, its flexible connections, sharp transient closing, and vehicle operational excitations, the door assembly is a primary source of noise and vibration in vehicles. It is a prime requirement to understand the NVH (Noise, Vibration, and Harshness) effect of doors on cars, their analysis, and ways to improve them. To understand the current status of the basic and advanced NVH analysis of the door, an extensive survey and detailed study were conducted. The primary focus is given to technical papers published related to noise/sound quality (SQ) over the last two decades, i.e., between 1999 and 2022. A total of 31 technical papers were scrutinised and summarised into different categories. Broadly divided into: the number of papers published each year, the Number of papers on types of SQ assessment, and the number of documents discussing SQ parameters. This study of the 31 papers published between 1999 and 2022 has provided a ready reference for the work done on sound quality, primarily related to vehicle and door NVH. The total number of parameters considered by different researchers and the approaches used by them to assess the psychoacoustic parameters of noise/sound. Ultimately, these parameters and their levels help determine the quality of the sound produced or generated by any source.

Keywords: NVH, Modal Test, Sound Quality Assessment, Vehicle Interior Noise, Psychoacoustics

I. INTRODUCTION

This paper aims to identify and review the literature on car door noise, sound quality evaluation, and application evaluation. A detailed scrutiny and analysis of relevant research work from the past two decades (1999-2022) has been done. The applicability and importance of car door sound quality, along with its top-level descriptors, are

depicted in the introduction. The car door is one of the most essential accessories of a car. The car's aesthetic design, passenger safety, car body reliability, car body vibrations, car noise, and the first interaction point for all human beings are all critical considerations. The door is the primary influencer of the above essential performance attributes. So, it is necessary to study and understand car doors. In the generic term, a car door means a complete assembly that includes the structure, latch, lock, glass regulator, all seals, mirrors, switches, and wire harness.

When considering the NVH of a car door, it is connected to human feelings, perception, and situational factors. All these tangible and intangible influencing factors and their effects are addressed under the head of sound quality. To address these factors and capture these intangible effects in objective terms, researchers have considered multiple aspects or parameters. These parameters are essentially the dominating variation within the overall noise and vibration of the door. These parameters mainly include Sound pressure level (SPL), Loudness, Sharpness, Roughness, Fluctuation strength, tonality, Timbre, Pitch, etc.

II. OBJECTIVE OF THIS RESEARCH WORK AND ITS NOVELTY

Out of 31 papers related to car door sound quality, each one has focused on particular parameters and has been evaluated using one or multiple techniques, such as actual measurement, CAE method, and jury method. All these parameters and their evaluation methods have been summarised in the respective papers. This literature study serves as a ready reference for evaluating the current status and identifying the gaps in car door sound quality (SQ) evaluations. This enables the establishment of a new methodology to assess the most critical parameters and suggests design changes to doors that will enhance the quality of sound and vibrations. To improve the sound quality of the car door, it is essential to understand the current state of technological advancements in this area. Statistical analysis of the studied literature is the most effective way to understand the current technological status regarding car door noise and sound quality.

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Fig. 1. Door Assembly on Car / Vehicle



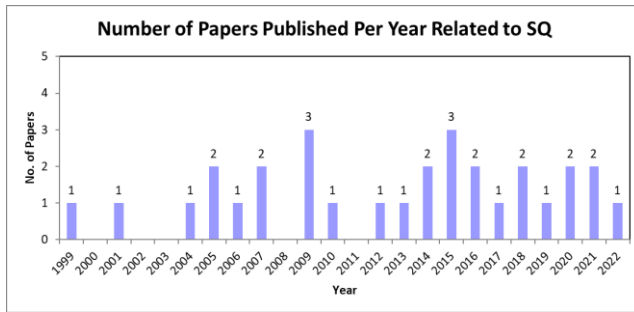


Fig. 2. Number of Papers Published Per Year Related to Sound Quality

A literature survey was conducted on car door sound quality, encompassing published papers from 1999 to 2022. A total of 31 papers have been studied and scrutinised in statistical and technical ways. Statistics of these 31 papers are that 2/3 of the documents have been published in the last decade, i.e., “2012 – 2022”, which indicates that recently more focus has been given on sound quality (Fig. 2).

The distribution of 31 papers, categorised by type of assessment, is as follows. Five papers on each of the below types are “virtual model development and correlation of results”, “SQ results comparison and use of regression method”, and “generic noise/ SQ simulation and correlation”. Eight papers on each of the below types are “generic noise/ SQ simulation”, and “generic descriptive on SQ” (Fig. 3 and Fig. 4).

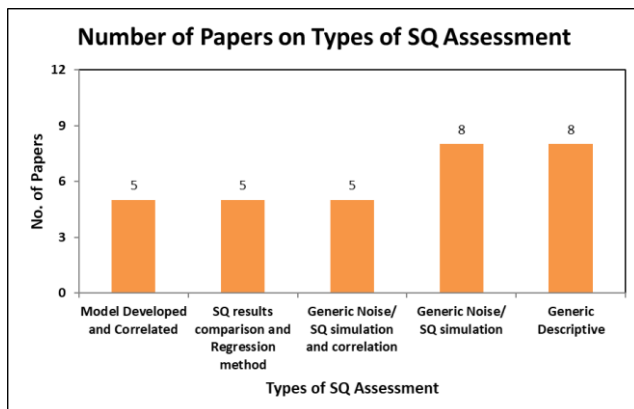


Fig. 3. Type of SQ Assessment

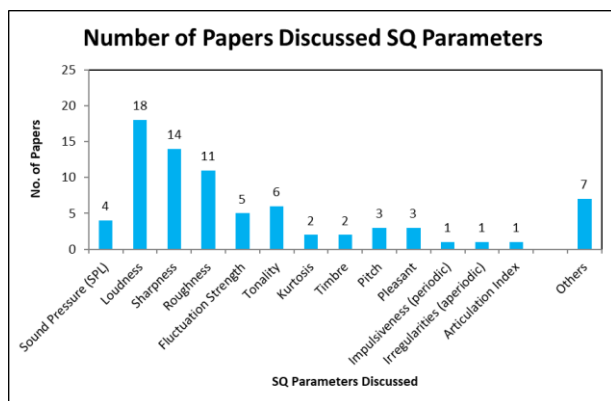


Fig. 4. SQ Parameters Discussed

At the top level, noise and vibration are considered a single attribute; however, a detailed study reveals that there are multiple variations of these attributes. To address these

variations and factors, and capture their intangible effects in objective terms, researchers have considered various aspects or parameters. These parameters are (1) Sound pressure level (SPL), (2) Loudness, (3) Sharpness, (4) Roughness, (5) Fluctuation strength, (6) Tonality, (7) Timbre, (8) Kurtosis, (9) Pitch, (10) Pleasant, (11) Impulsiveness, (12) Irregularity, (13) Articulation Index, etc. This literature survey indicates that most researchers have focused on loudness, sharpness, and roughness, with 50% of researchers performing analysis and correlation of their models for subjective evaluation (Fig. 4).

Based on the above literature study and statistical analysis, it is concluded that there is scope for further work in the actual implementation of the evaluation method and the development of virtually implemented models. To achieve this, various designs and design modifications should be implemented to enhance sound quality in terms of the listed parameters. This is an encouragement for new work and will be considered in my future research endeavours.

III. LITERATURE REVIEW FROM THE PERSPECTIVE OF SOUND QUALITY

Sung-Yuk Kim et al [1], 2022: Carried out the sound quality parameter study to find the relation between the frequency and sound quality of the small electric motor used for automotive interior parts operations. A comparative study was conducted on two types of motor designs. Twelve characteristics were subjectively assessed with 12 pairs of adjectives. Twelve operating conditions of motors are used to record the sounds. The sound of each condition was recorded three times, resulting in 36 sound recordings (Fig. 5), which were then heard by 100 students from a medium age group of ~30 years. The students were asked to express their opinions using 12 adjectives. The same data was evaluated by 40 students, with an average age of 25 years, who provided recorded feedback about the 12 pairs of adjectives on a 10-point scale. Subjective sound tendency was analysed and confirmed using a polarity profile and regression method. This method demonstrates high accuracy in predicting sound quality parameters, including loudness, sharpness, roughness, fluctuation strength, and tonality.

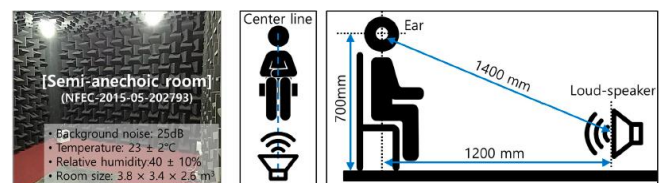


Fig. 5. Sound Quality Subjective Evaluation Set-up[1]

Kun Qian et al [2], 2021: Considering psychoacoustic parameters of sound quality (SQ) as an index of evaluation of interior noise of a pure electric vehicle. Transfer path analysis (TPA) and transfer path synthesis (TPS) techniques are used. Based on TPA and TPS, a new virtual model was designed to synthesise interior noise. The synthesis technique predicts that each noise component contributes, as demonstrated by the new SQ separation technology.

As a standard analysis, the effect of each excitation and transfer path was tested using a new model and the quality of the objective parameters was verified. Finally, researchers validated the results of the latest virtual model through an experimental comparison. There is better agreement between the new synthesis model and experimental results (Fig. 6).

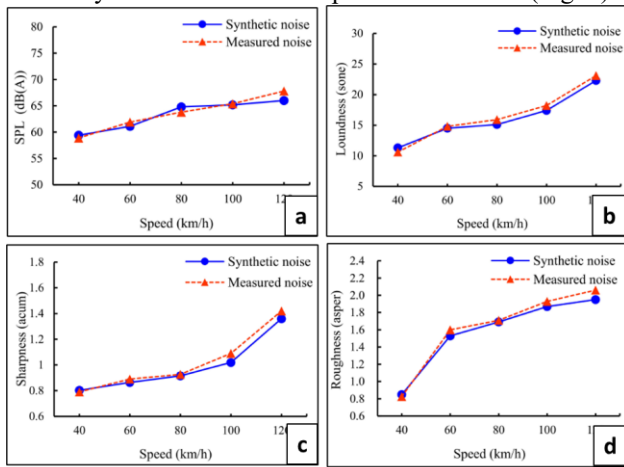


Fig. 6. Psychoacoustic Parameter Comparison of Sound Quality : (a) Noise, SPL, (b) Loudness, (c) Sharpness, and (d) Roughness [2]

Mehdi POURSEIDREZAEI et al [3], 2021: Developed real-time sound quality control model. It's based on two main criteria of evaluation. First is the optimal analysis wavelet transform (OAWT), and second is the particle swarm optimisation, which is related to the initial weight. The developed model is capable of extracting a matrix of sound quality parameters based on the energy, mean, and standard deviation from the input signal's scalogram. These matrices are fed to the neural network input to determine psychoacoustic parameters, such as loudness, sharpness, roughness, and tonality, which are used for sound quality assessment. The suggested model results show close agreement with psychoacoustic models of sound quality metrics (Fig. 7).

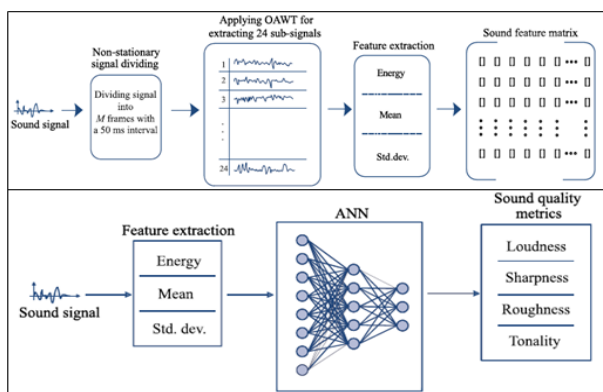


Fig. 7. OAWT and OAWT-BPNN Model for the Extraction and Prediction of Psychoacoustic Matrix [3]

Gao Yunkai and Liu Zhe [4], 2020: A Study was done on the basic parameters of sound at the driver's ear location for the door closing operation. The main force was given based on the actual excitation applied or transferred during the door closing test. Test FRF and simulation FRF for the concentrated impact loads are calculated. Both FRFs are

compared and correlated. Concerning correlated simulation FRF results and the use of the inverse matrix method, the actual excitation load has been predicted. Lastly, using predicted excitation loads and the boundary element method (BEM), the sound level is calculated at the driver's ear location. Sound, SPL at the driver's ear location of BEM and Test, have better consistency (Fig. 8). This can be applied to other door closing sound evaluations.

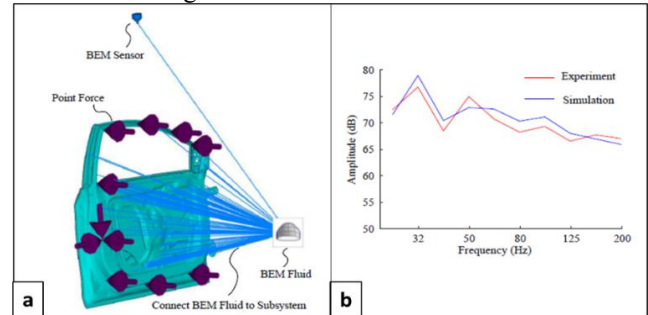


Fig. 8. (a) BEM simulation and (b) SPL Comparison Curve of Test and Simulation [4]

Erkut Yalcin et al [5], 2020: Assessed the car door model similar to the other researcher but with a different analysis type, i.e., the transient analysis for noise calculation using a vibro-acoustic finite element model. Experimentally, exterior sound was measured in the time domain outside the door for door-slam loading. To compare the experimental results with the simulation results, a vibro-acoustic analysis was performed to estimate the sound in the time domain for door slam loading conditions. Sound quality results, in terms of sound pressure, SPL of the test and vibro-acoustic BEM, were well correlated (Fig. 9). The same steps or methodology were used for studying design sensitivity and utilising the same vibro-acoustic model. The author recommends this methodology to assess design changes during the product development stages.

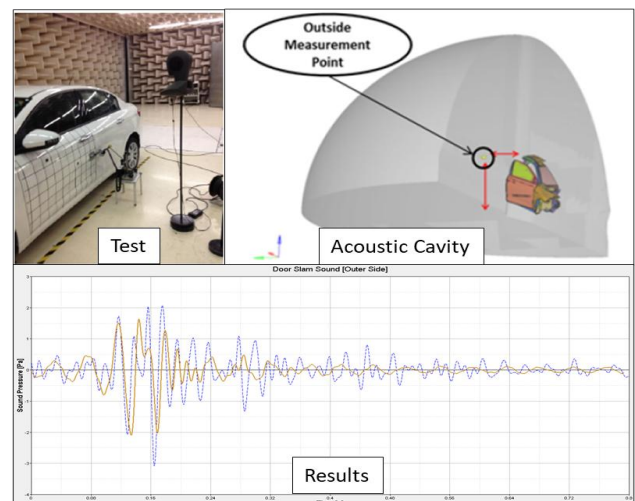


Fig. 9. (a) BEM simulation and (b) SPL Comparison Curve of Test and Simulation [5]

Woonjoon Kim et al [6], 2018: Research work was carried out basically to know the comfort and affective parameters related to the door opening noise. They recorded the fourteen different vehicle door opening noises. The jury and participants evaluated the recorded data based on a standard questionnaire prepared by the researchers. The questionnaire's primary focus was to find auditory pleasantness in terms of attributes such as "Load", "Sharp", "Rough", "Clear", and "Satisfy". In the next stage, the same noises were assessed in terms of psychoacoustic parameters such as "Loudness", "Sharpness", "Roughness", "Fluctuation Strength", and "Tonality". Finally, authors used the regression method and developed a model that predicted the subjective response to door opening noise. Based on this noise evolution study, they concluded that auditory loudness has a significant effect on auditory pleasantness.



Fig. 10. Noise Recording in Anechoic Chamber [6]

Xiaoping Xie et al [7], 2018: The vehicle door closing noise signals are of a shock nature. Xiaoping and his team worked on these signals to evaluate their different aspects. As it is transient, its effects are intangible to human beings. Researchers proposed a method to extract the psychoacoustic parameters of non-stationary vehicle door closing sound quality. This method was used to evaluate the transient time-frequency parameters as objective parameters. Measured signal data were post-processed using empirical mode decomposition (EMD) and intrinsic mode function (IMF) analysis, and then examined through spectral analysis. Based on the human auditory frequency range, some of the IMF components are eliminated, and practical IMF components are extracted as analytical frequency bands using the complex analytic wavelet. With the proposed method, psychoacoustic parameters and energy coefficients were well correlated (Fig. 11).

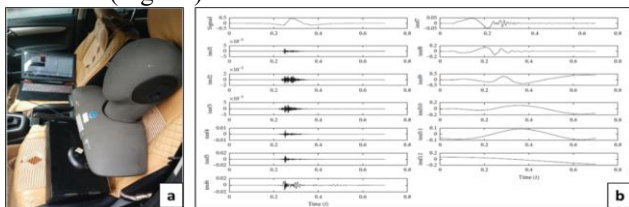


Fig. 11. (a) Noise Collection Set-up and (b) Each IMF Component of Sample S1 as an Example [7]

Mosquera-Sanchez et al [8], 2017: Inclusion of electric drive to make existing vehicles like hybrid electric vehicles (HEVs). They studied the effects of electrification and noise in a broader frequency band, primarily at higher frequencies. It presents the framework for improving the sound quality of the hybrid electric powertrain noise inside the vehicle compartment. This technique helps reduce the amplitude of the tones at the optimisation stage to achieve a better fit of the auditory experience. Here's the consideration that

psycho-acoustic parameters, such as loudness, roughness, sharpness, and tonality, are most closely related to sound quality. The proposed framework is verified by experimental results, which show a total success rate of over 90%, indicating that the proposed method is promising (Fig. 12).

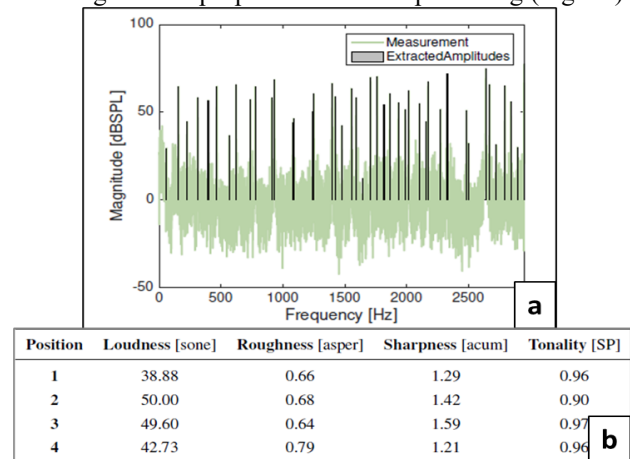


Fig. 12. (a) Function of the Measured Sound and (b) SQ Score of the Sample Sound [8]

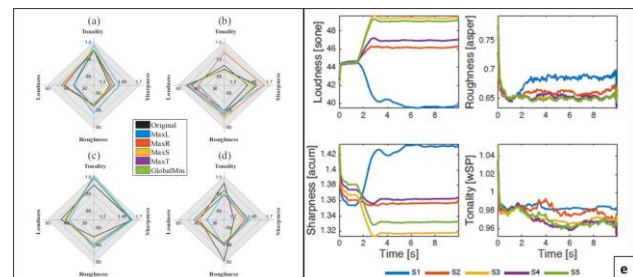


Fig. 13. (a) – (d) Radar Plots of the SQ Parameters and (e) Time-Domain SQ Parameters [8]

M. Farid Aladdin et al [9], 2016: Researchers evaluated the psychoacoustic response of sound quality in terms of loudness and sharpness. It is an owner's perception of their car, which is often biased towards comfort. To evaluate this subjective phenomenon or response in psychoacoustics, it is required to account for background effects and tendencies. Each owner of a different vehicle type (Compact, Sedan, and Luxury) has distinct expectations regarding interior sound quality, based on their individual preferences. Hearing sensitivity and perception are based on their day-to-day experience under real-world usage. To do this, the researcher has designed a questionnaire based on three different aspects or categories: first, demographic information; second, comfort level inside the cabin; and third, comfort level related to loudness. A couple of example sounds were provided, and we were asked to form a judgment about the sound/data. In this survey, a total of 42 participants (30 male and 12 female) participated. The sound quality response from this survey of 42 participant owners was that 80% of owners feel comfortable with their own vehicle's interior sound quality in terms of loudness and sharpness (Fig. 14). The results show a clear bias indication based on their driving experience.

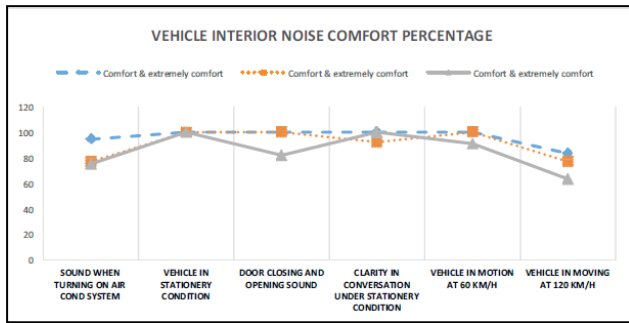


Fig. 14. Vehicle Interior Noise Comfort Percentage by Car Type under Different Conditions [9]

Zutong Duan et al [10], 2015: These researchers used Back Propagation Neural Network for Sound Quality Prediction (BPNN-SQP). They have used the whole vehicle interior noise as an example source, considering four different operating conditions. Noises from operating conditions of vehicle idling, Constant speed operation, vehicle acceleration, and vehicle speed braking. Annoyance values of interior noises generated from the operation mentioned above are fed into the BPNN-SQP model, and the output is calculated in terms of annoyance values in the form of A-weighted sound pressure, Roughness, Articulation Index, and Sharpness. From the same samples, these objective psychoacoustic parameters and subjective annoyance results are used as input and output, respectively. Test results under the same operating conditions were correlated with the production of BPNN-SQP (Fig. 15). The predicted annoyance results show an accuracy of 95.57%. This suggests that the BPNN-SQP model can be utilised to assess the noise annoyance associated with various operating conditions and design evaluations.

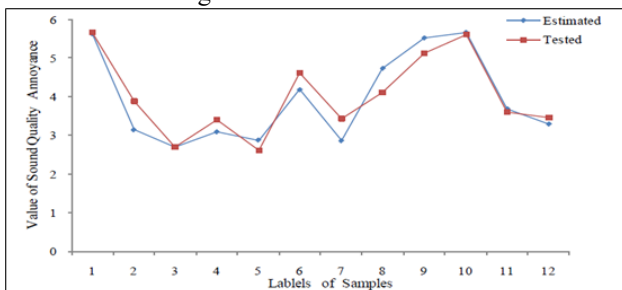


Fig. 15. Comparison of BPNN-SQP Estimated and Test Results [10]

Zongcai Liu et al [11], 2015: These researchers worked on the effect of train doors closing on sound quality, due to the short closing time and high pressure. There were multiple sharp crests at low frequencies, and the sound range was 50 Hz to 3000 Hz. A sound objective assessment was conducted using psychoacoustic sound quality parameters, including A-weighted sound pressure level, loudness, sharpness, roughness, and fluctuation, which represent people's perceptions of the sound. Different door sounds were evaluated, and a discrepancy was found between the actual feelings about sound and the A-weighted sound pressure level. However, loudness and roughness predictions were close to the subjective feelings. Going forward, specific loudness was calculated, which effectively represents the sound's frequency. The particular loudness curve shown (Fig. 16) from 0 to 3 bark value is high for doors no. 1 and no. 4,

and is aligned with the door closing instant pressure.

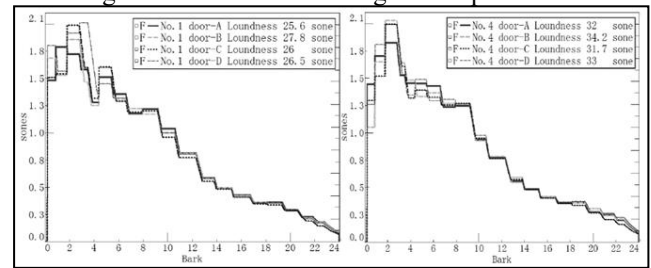


Fig. 16. Specific Loudness Curve of Door No.1 and Door No.2 Sound [11]

Hyeonho JO et al [12], 2014: A Study was done to develop the sound quality evaluation index for door latch operation sound (Fig. 17). Sounds of different operating conditions were studied by a jury and, based on feedback index, were developed to evaluate the door latch operational sound. After studying the sound source, it was concluded that the door latch sound was generated by airborne noise, rather than the effect of the noise path. The developed index was utilised as a tool for optimising door latch sound quality.

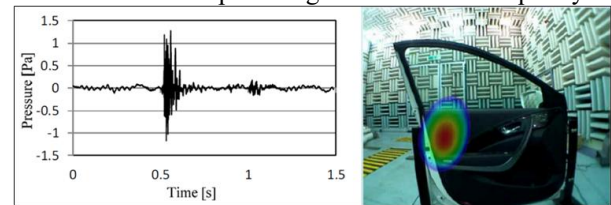


Fig. 17. Door Latch Opening Sound Spectrum and Visualisation [12]

Marie-Celine Bezat et al [13], 2014: A detailed investigation of door sounds has been done (Fig. 18). To address these results of jury perception, naïve listener, ecological parameter study, linear regression and empirical mode decomposition are used. After this study, they attempted to identify the relationship between the two. Finally, they concluded that the analytical evaluation and perception relation are more relevant and need to be established, which will speak to the quality of door closing noises.

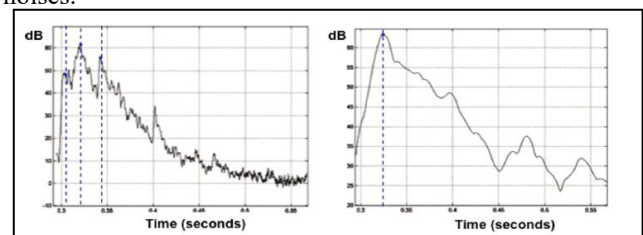


Fig. 18. Contribution to Door Noise from (a) Lock and (b) Door Closure [13]

Etienne Parizet et al [14], 2013: To meet the standard requirement for door sound quality. Researchers added multiple parameters, starting with cultural differences, door closing speed, sound pairing, sound sample size, perceptual space, and verbalisation of sound. Considering the above parameters, the different door seals were evaluated, and a demerit score model was developed to assess each seal variation (Fig. 19).

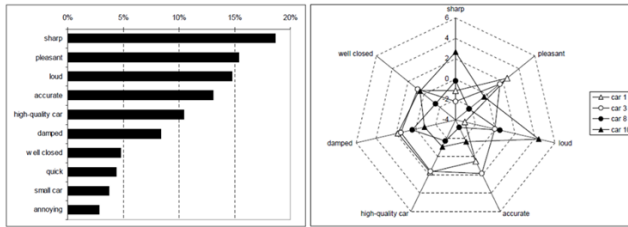


Fig. 19. Sound Evaluation Parameters [14]

G. Vollandri et al [15], 2012: The team worked on the power window subjective and objective test with different conditions in terms of SPL (dBA). Test results are displayed in real-time (Fig. 20) and compared with generic threshold values. Apart from tests, researchers have mentioned general definitions of psychoacoustic parameters of sound quality, such as loudness, sharpness, roughness, fluctuation strength, and kurtosis. At the same time, test conditions were simulated digitally, and it was concluded that door panels and masking had a greater effect on acoustic parameters. Finally, digital simulation and jury test are also equally crucial in conforming to the behavioural significance of power window sound quality assessment.

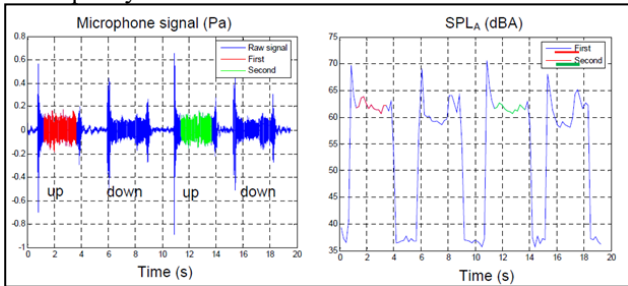


Fig. 20. Real Time Pressure and SPL [15]

M. Ercan Altinsoy [16], 2010: The Author worked on the vehicle noise under the two conditions, i.e., stationary and in-stationary. Studied the effect of “Engine Start – in-stationary” and “Idle – quasi-stationary” conditions sequentially on overall vehicle noise judgment. To conclude this work, psychoacoustic tests were conducted using binaural head recordings of both conditions for 12 vehicles of different brands. Recorded sounds are presented to the jury and asked to describe these sounds as part of a subjective test (Fig. 21). Both condition results are evaluated sequentially, and the test experiments provide hints of multiple events.

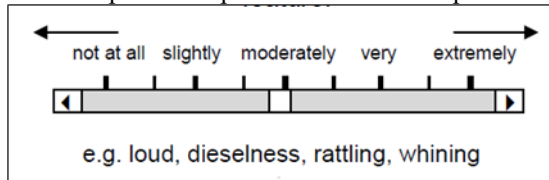


Fig. 21. Verbal Assessment Interface [16]

Gabriella Cerrato et al [17], 2009: Gabriella and team described basics related to the sound quality with examples and at the same time, summarised the objective parameters and metrics used for vehicle sound quality assessment. While doing this, researchers described the techniques used to finalise the metrics and correlation of these metrics based on customer subjective (jury perceptions) feedback (Fig. 22). This paper covers sound quality related to “Vehicle Harmony, Electric Vehicles, Internal combustion engine with diesel fuel, Exhaust and Intake system, tire/ Road noise, and

Wind noise”. These developed techniques and metrics are subject to change over time and require regular review and modification to keep pace with current requirements.

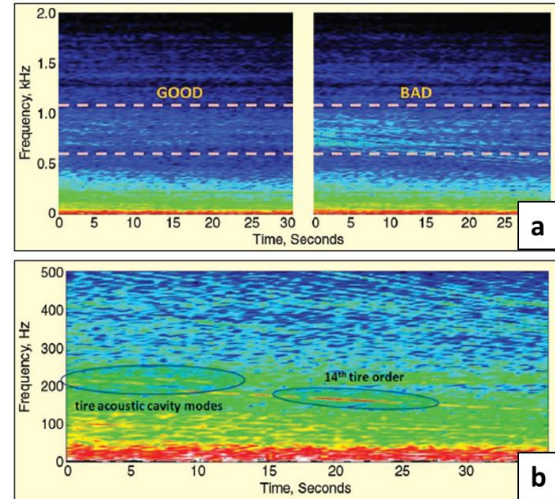


Fig. 22. Examples of (a) Good and Bad Road Noise Quality, (b) Poor Sound Quality Due to Low Frequency Tire Noise [17]

Hugo Fastl [18], 2009: Author assessed the loudness calculation methods mentioned in the standard, ANSI S3.4-2007, DIN 45631 (1991), and DIN 45631/A1 (2008). First, verified the stationary/ pure tone/ pink noise loudness calculated by ANSI S3.4-2007, and 45631 (1991). It should be the same, but it is affected by subjective annoyance value, levels, and reach factor (Fig. 23). In the case of a time-varying loudness function, such as a Jackhammer, the calculation should be done using DIN 45631/A1 (2008).

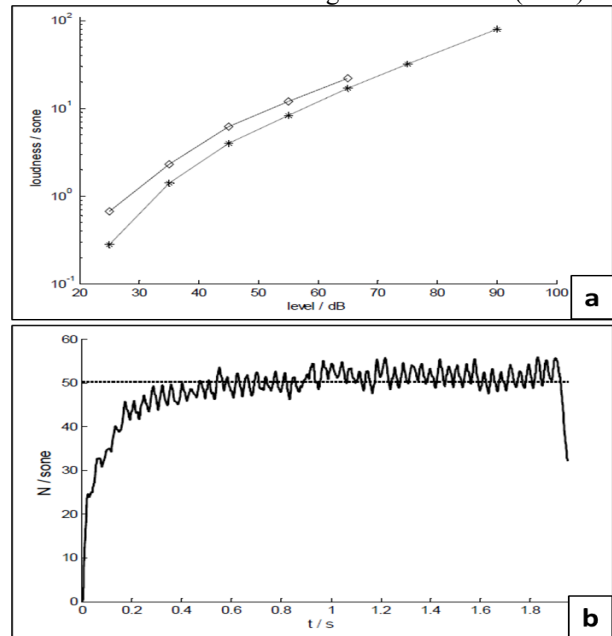


Fig. 23. Loudness of (a) Pink Noise as a Function of its Overall Level, (b) Jackhammer Noise as a Time Function [18]

Gabriella Cerrato et al [19], 2009: Gabriella and team described basics related to the sound quality with examples such as accessories to the vehicle. At the same time, it summarises the objective parameters and metrics used for assessing the sound quality of accessories. Briefed on the techniques used to finalise the metrics and correlation of these metrics based on customer subjective (jury perceptions) feedback (Fig. 24). This paper covers sound quality related to “Vehicle BSR (Buzz, Squeak and Rattle) and accessories (Brake, Seat)”. These developed techniques and metrics are subject to review and modification based on the current requirements.

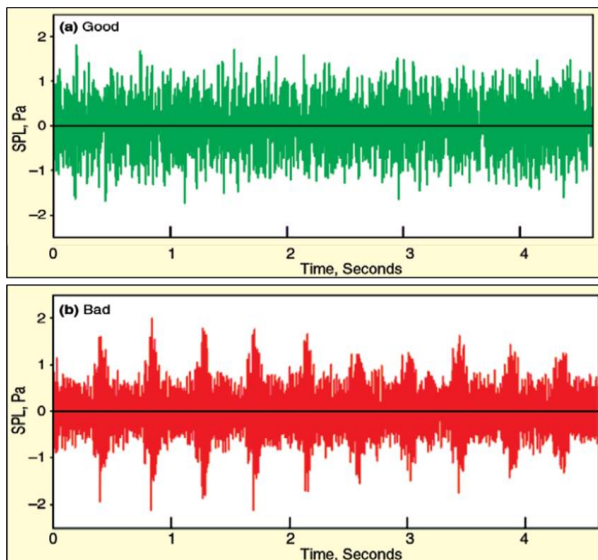


Fig. 24. Sound Pressure of Good and Bad Seat Adjuster in Time Domain [19]

Gabriella Cerrato et al [20], 2007: This is one of the articles from a series of four articles that talk about the process of sound/ vibration quality and give a thorough understanding of the basics of sound/ vibrations of any product. The outcome of the first is the five-step general process. Second article brief on the sound/vibration quality. It will review all findings related to the targets and summarise an assessment strategy. The third article summarises the targets for consumer products and medical equipment. The fourth article discusses advanced techniques related to sound and vibration quality. Based on the reviews of relevant literature, key strategies have been summarised (Fig. 25).

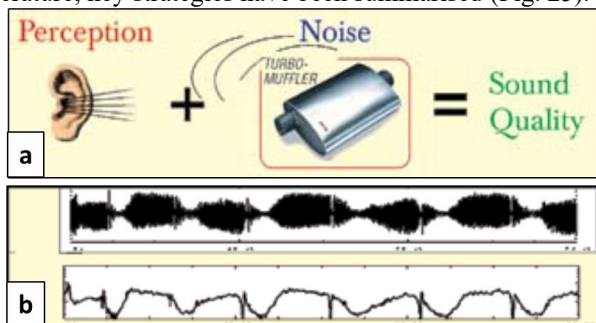


Fig. 25. (a) Ingredients of Sound Quality, and (b) Steering Wheel Vibrations (Time History and RMS Envelope) [20]

Fastl Hugo et al [21], 2007: Psychoacoustic parameter

loudness was used to verify the noise reduction because of the sound-absorbing road surface. In this study, the pass-by noise and loudness of the car were estimated using the procedure outlined in ISO 10844. Sounds of five different (ISO, A1, A2, and A3 of different absorbing surfaces and B, a conventional non-absorbing surface) road surfaces effects were measured and evaluated in term of loudness and sharpness and compared with prediction (Fig. 26). Finally, this study predicts that subjective evaluations and measured percentile loudness N5 have good agreement.

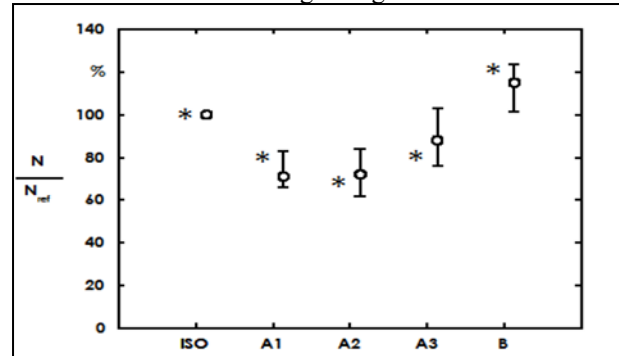


Fig. 26. Psychoacoustic Experiments (Circles) and Physically Measured Values of Percentile Loudness N5 (stars) [21]

Sonoko Kuwano et al [22], 2006: A study was conducted to establish the relation between the subjective and mental impressions or images of the quality of sound generated while closing the car door. As an experiment, eleven different car door closing sounds were recorded using an acoustic head, and the same sounds were heard by ten German and Japanese participants in the age group of ~ 25–35 years. Fifteen paired adjectives on a 7-point scale were used to report the responses. The same sounds were evaluated using a semantic differential (Fig. 27). Culturally, the pleasant impression results of German and Japanese experts showed good agreement regarding the car door sound quality.

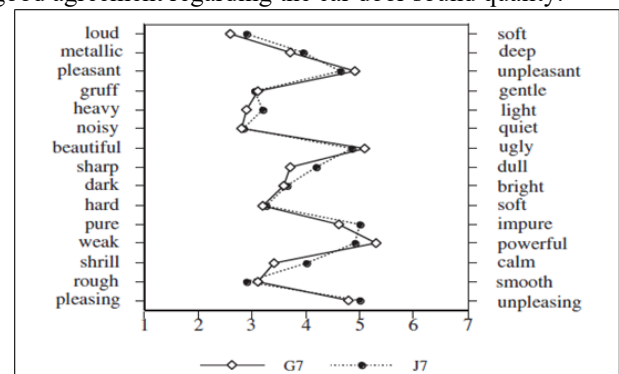


Fig. 27. Results of Best Correlated Sound Profile [22]

J.K. Lee et al. [23], 2005: The car interior noise was tested, and sound quality and psychoacoustic parameters were correlated. The vehicle was tested for “wide-open-throttle” and “constant-speed” conditions to measure objective parameters. The same data has been evaluated using a subjective method by 17 test engineers, who rated their perception on a scale of 0 to 10.

The outputs in terms of psychoacoustic parameters from the objective and subjective tests were correlated. The most critical parameters were identified, and a multi-factor regression equation (Fig. 28) was established to predict sound quality. Output sound quality indexes were compared with previously established indexes and matched well with human hearing predictions.

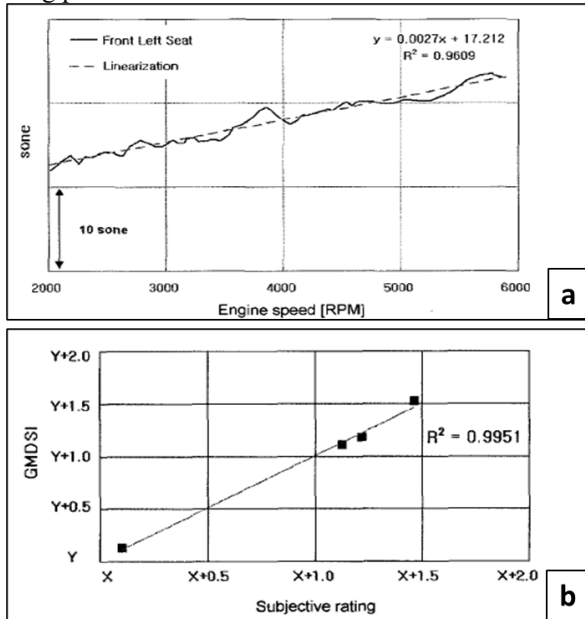


Fig. 28. (a) Level of Zwicker's Loudness and (b) Correlation of Subjective Evaluation for Wide-Open Throttle [23]

Anders Skold et al [24], 2005: Researchers work on the vibration of the steering and seat for engine idle and the car passing the bridge joint. Vibrational Stimuli were measured to determine their influence on sound quality. Measured vibration data was modified and presented to 44 jury members. Jury results indicate a strong correlation between vibration and sound perception under steady-state and transient conditions (Fig. 29).

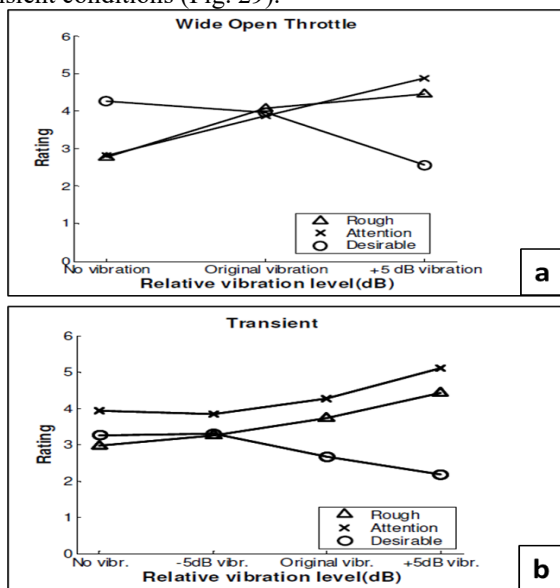


Fig. 29. (a) Rating for the WOT and (b) Transient Stimuli based on Three Adjectives [24]

Martin Pflueger et al [25], 2001: Martin and team explained the new software developed by AVL. The AVL VOICE software was designed to assess passenger vehicle interior noise in terms of sound quality perception (Fig. 30). Mainly, this software can measure and predict human feelings in an objective form. This development was undertaken under the heading of "Sound Quality Map". Right now, it addresses the feeling in terms of "Annoyance Index", "Level of Annoyance", "Sporty", "Luxurious", "reliable", and "Powerful". The same software has been implemented for commercial vehicle applications to assess sound quality objectively.

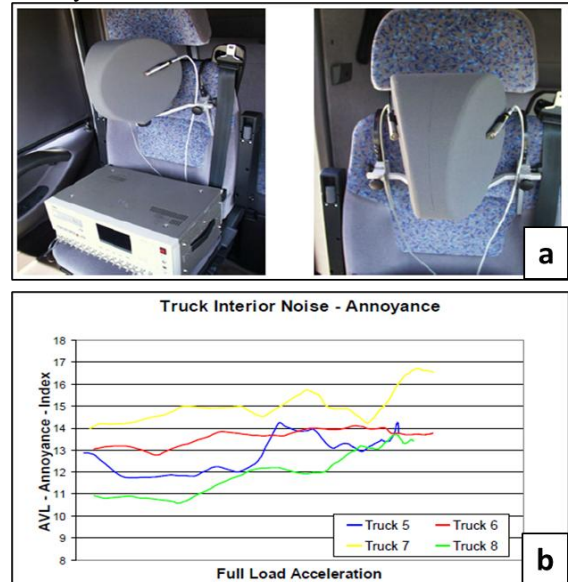


Fig. 30. (a) AVL Artificial Head, (b) Annoyance [25]

Patric Susini et al. [26], 1999: A study revealed approaches to improve sound quality by considering multi-dimensional acoustic parameters that address auditory perception. To achieve this preference, a map was created to account for the multiple dimensions. The technique CLASCAL reveals these multi-dimensional parameters from a set of sample sounds—the dissimilarity feedback for all the samples that were listed and evaluated. Feedbacks were correlated with perceptual dimensions, which showed strong agreement. It represents multidimensional sound samples and predicts a close relationship between perceptual and acoustic properties. It also defines properties of certain sounds that affect perceptual and comparative feelings.

Marek MORAVEC [27], 2019: The Paper describes the psychoacoustic parameters and equipment used for the evaluation of acoustic parameters. Additionally, we discussed the general procedure for evaluating sound quality, which involves both measurement (objective method) and jury testing (subjective method). Sound quality parameters related to electronic home appliances and their definitions. Ultimately, it concludes that customer expectations can be more closely addressed through feedback provided by a human ear.

Tomasz Letowski [28], 2016: Tomasz worked on sound quality parameters such as loudness, pitch, timbre, duration and spaciousness to



define and describe them.

All these parameters were compared with each other. After that, various types of sound quality have been described and finally summarised in terms of the sound and sound quality images or characteristics of two sound sources. All these aspects were combined in a sound assessment system – MURAL. The future success of this system depends on aligning and upgrading current requirements to meet future needs.

Daniela Maffiodo et al [29], 2019: The following applied standards were described in terms of sound and sound quality. ISO 532 and DIN 45631 provide the graphical and computational method to calculate the sound loudness. ISO 226 provides equal loudness contours, ISO 3745 establishes standards for noise sound pressure levels, and DIN 45631/A1 offers a method for calculating time-varying sound levels. ANSI S1.11 and IEC 61620 specify one-third octave band filtering. Using the above standards, the electronic locking and unlocking noise loudness index of the steering column was evaluated, and the procedure is outlined.

Klaus Genuit [30], 2004: Klaus, put all the general information about the sound quality. Starting with the meaning, definition, and listing of influencing factors: physical sound, feeling, psychoacoustic perception, and psychological evaluation. Sound quality is a multidimensional phenomenon and should be addressed in all aspects. To address this, an artificial head with multiple channels enables analysts to perform an accurate assessment of the noise data. An introduction to subjective feelings and judgmental opinions is essential for converting sound quality into practical solutions.

Dr. Karthick Jayaram et al [31], 2016: This paper talked about the aesthetic quality of the passenger vehicle, not the sound quality. The primary focus and priority areas of interfaces are the "Front-Rear Door and Headlamp-Hood", "Windshield-Roof and A-Pillar-Roof", and "Door-Rocker Mounting and Hood-Grille" areas. Based on the requirements, the gap between the above-listed pairs is maintained tightly in design and manufacturing (Fig. 31). These gaps and flushes are effectively achieved through tolerance management. Hinge positions, striker-hinge adjustment, and door hemming achieve superior aesthetics. These interfaces provide side closures with exceptional aesthetics and a royal look, which will add a winning edge to the saleability of the vehicles.

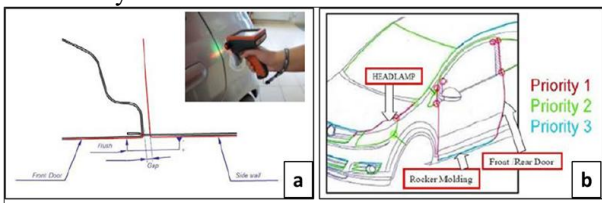


Fig. 31. (a) Gap and Flush Measurement, (b) Tolerance Management Priority Areas [31]

IV. SOUND QUALITY RESULT AND DISCUSSION

Most researchers focused on simulating the sound quality of car doors and correlating objective and subjective parameters. All researchers measured objective parameters in terms of sound, and subjective parameters were assessed based on jury feedback. After receiving the jury feedback, the

same parameters were correlated with the output of the developed virtual model and the multi-parameter regression model.

Some researchers have only simulated sound quality and compared it with either reference results or the results of different designs within the same product category.

Some of the papers describe the sound quality parameters, definitions, characteristics, tentative frequency ranges, and methods for measuring and evaluating them.

It is good that maximum work or results have been correlated either by virtual tools or actual jury tests.

V. CONCLUSION

The door is one of the primary sources of structural noise in the car. Its noise behaviour is transient and of short duration, so it has many variations that need to be addressed to improve the sound quality. Statistical analysis suggests that Sound Pressure (SPL), loudness, sharpness, roughness, fluctuation strength, and tonality of noise are the primary parameters to focus on to achieve better sound quality. All mentioned parameters address sound quality, but we need to determine the relationship between them and identify the relationship between these parameters and frequency or frequency band. These relations may help address sound quality issues and facilitate an in-depth study.

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ABBREVIATIONS

NVH – Noise, Vibration, and Harshness
FEM – Finite Element Model
BEM – Boundary Element Model
FRF – Frequency Response Function



CAE – Computer-Aided Engineering
 SPL – Sound Pressure Level
 SQ – Sound Quality
 TPA - Transfer Path Analysis
 TPS - Transfer Path Synthesis
 OAWT - Optimal Analysis Wavelet Transform
 EMD - Empirical Mode Decomposition
 IMF - Intrinsic Mode Function
 HEV - Hybrid Electric Vehicles
 BPNN - Back Propagation Neural Network
 SQP - Sound Quality Prediction
 BSR - Buzz, Squeak and Rattle
 DIN – Director Identification Number
 ANSI – American National Standards Institute
 ISO - International Organization for Standardization
 RMS – Root Mean Square
 dBA – decibels (A – scale)

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