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 in-tangible effect. NVH is directly and indirectly connected to the psychoacoustics of human beings and lives. As a part of the advanced NVH analysis, the effects of noise have been studied in terms of psychoacoustic parameters such as loudness, sharpness, roughness, fluctuation strength, tonality, etc. Car door or door assembly is an integral part of the car or vehicle. The door is softly and flexibly connected to the main body of the vehicle; it protects passengers from weather effects and accidental impacts. Because of the inherent flexibility of the door, its flexible connections, sharp - transient closing, and vehicle operational excitations, the door assembly is one of the main sources of noise and vibration in vehicles. It is a prime requirement to understand the NVH effect of doors on vehicles, its analysis and ways of improvement. To understand the current status of the basic and advanced NVH analysis of the door, an extensive survey and in detail study was conducted. The main focus is given on technical papers published related to noise/ sound quality (SQ) during the last two decades, i.e., between 1999 – 2022. Total 31 technical papers were scrutinized and summarized in different categories. Broadly divided into: the number of papers published each year, Number of papers on types of SQ assessment, and the number of papers discussed SQ parameters. This study of these 31 papers published between 1999 – 2022 has given a ready reference for the work done on sound quality, mainly related to the vehicle and its door NVH. The total number of parameters considered by different researchers and approaches used by them to assess the psychoacoustic parameters of noise/ sound. Finally, these parameters and their level help to 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 is dedicated to find and study 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 and their top-level descriptors have depicted in the introduction. The car door is one of the key accessories of the car. The car aesthetics design, passenger safety, car body reliability, car body vibrations, car noise and first interaction point of all human beings is the car. The door is the major influencer to the above important performance attributes. So, it is necessary to study and understand car doors. In the generic term car door means, it is a complete assembly which includes structure, latch, lock, glass regulator, all seals, mirrors, switches and wire harness, etc.

When we think about the car door NVH, it connects to the human being feelings, perception and situational effects. All these tangible and intangible influencing factors and their effects are address under head of sound quality. To address these factors and capture these intangible effects in objective terms, researchers have considered multiple aspect or parameters. These parameters are nothing but dominating variation within the overall noise and vibration of door. Mainly these parameters are 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 evaluated using one or multiple techniques, such as actual measurement, CAE method, jury method. All these parameters and their evaluation methods have been summarised in respective papers. This literature study is a ready reference to find the car door sound quality (SQ) evaluation's current status and present gap. This gives way to setting up the new methodology to evaluate most concerned parameters and helps to suggest design changes to doors which will improve the quality of sound and vibrations.

To work on the car door sound quality, first understand the current status of technological developments. Statistical analysis of studied literature is the right way to understand the current technological status related to car door noise/ sound quality.

Fig. 1. Door Assembly on Car / Vehicle

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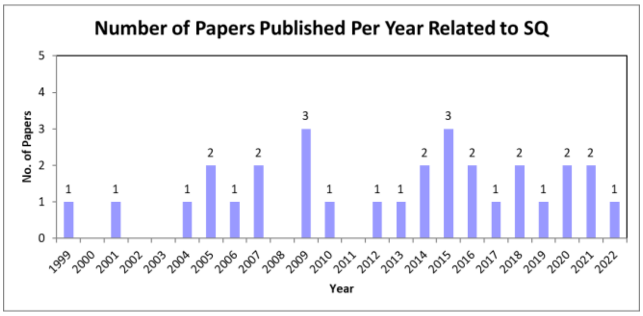

Fig. 2. Number of Papers Published Per Year Related to Sound Quality

A literature survey is done related to car door sound quality, which included published papers between 1999 – 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 papers 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 based on types 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).

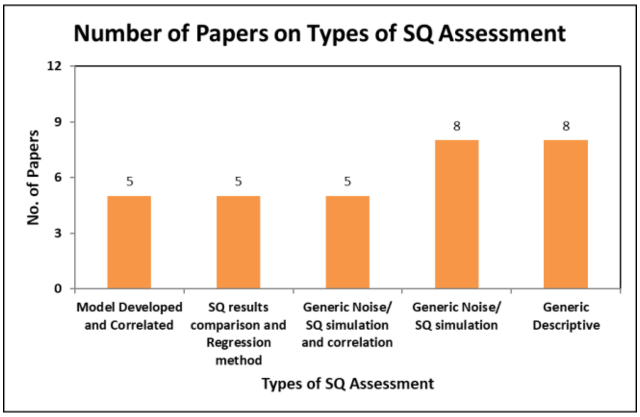

Fig. 3.Type of SQ Assessment

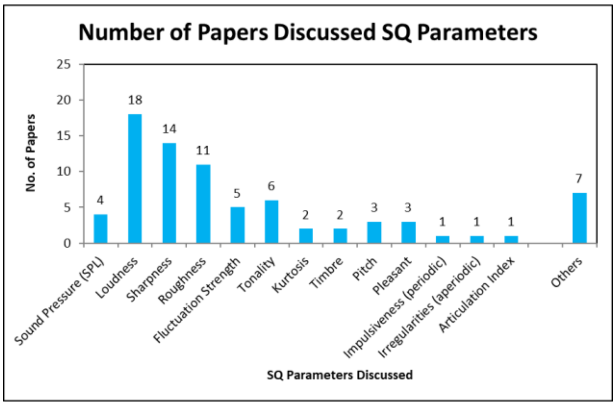

Fig. 4. SQ Parameters Discussed

At the top level, noise and vibration are a single attribute but, a detailed study reveals that there are multiple variations. To address these variations/ factors and capture these intangible effects in objective terms, researchers have considered multiple 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 depicts that most of the researchers worked on loudness, sharpness, roughness and 50% of researcher have done analysis and correlation of their used/ virtually developed model for subjective evaluation (Fig. 4).

Based on the above literature study and statistical analysis, it is concluded that there is scope to work in actual implementation of the evaluation methos and virtually developed models. To do these, different designs and design changes should be implemented for better sound quality in terms of listed parameters. It is encouragement for new work and will be considered in my future research work.

III. LITERATURE REVIEW IN PURSPECTIVE 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. State forward comparative study was conducted of two types of motor designs. 12 characteristics were subjectively assessed with 12 pairs of adjectives. 12 operating conditions of motors are used to record the sounds. The sound of each condition was recorded three times so that 36 sound recordings were collected (Fig. 5) and heard by participated 100 students of medium age group of ~30 years and asked, the opinion in term of 12 adjectives. The same data was evaluated by 40 students of average age 25 years, who given recorded feedback about the 12 pairs of adjectives on a scale of 10-points. Subjective sound tendance was analysed and confirmed with polarity profile and regression method. This method shows high accuracy in prediction of sound quality parameters such as loudness, sharpness, roughness, fluctuation strength and tonality.

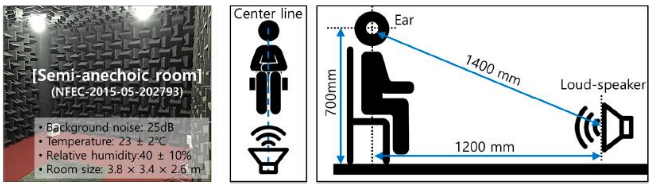

Fig. 5. Sound Quality Subjective Evaluation Set-up[1]

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 do the synthesis of interior noise. Synthesis technique predicts that each noise component contributes and it is demonstrated by new SQ separation technology.

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

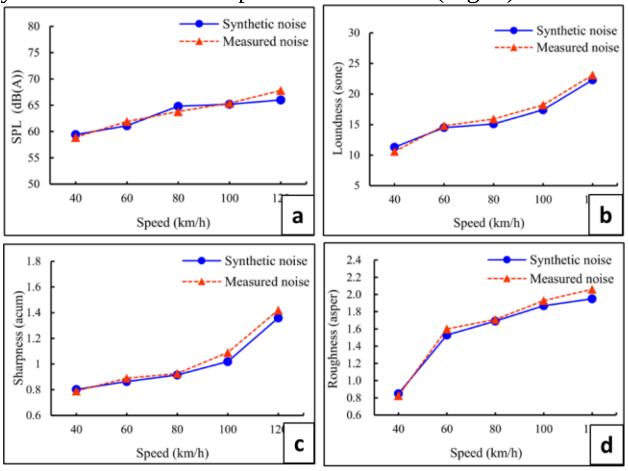

Fig. 6. Psychoacoustic Parameter Comparison of Sound Quality : (a) Noise, SPL, (b) Loudness, (c) Sharpness, and (d) Roughness [2]

Mehdi POURSEIEDREZAEI 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 optimization, which is related to the initial weight. The developed model is able to extract the matrix of sound quality parameters based on the energy, mean, and standard deviation from the input signal scalogram. These matrixes are fed to the neural network input to find out the psychoacoustic parameters such as loudness, sharpness, roughness, and tonality, which are used for sound quality assessment. Suggested model results have close agreement with psychoacoustic models of sound quality metrics (Fig. 7).

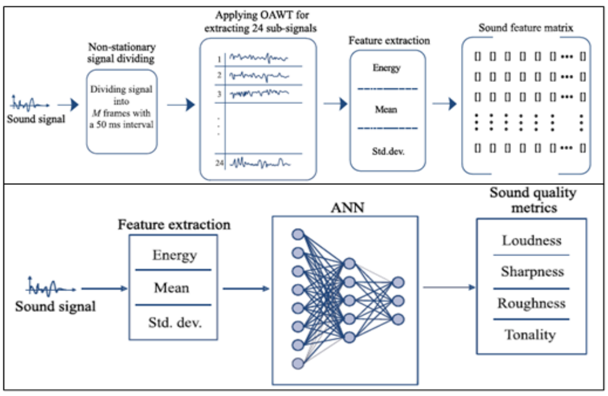

Fig. 7. OAWT and OAWT-BPNN Model for the Extraction and Prediction of Psychoacoustic Matrix [3]

Gao Yunkai and Liu Zhe [4], 2020: Study was done on the basic parameter of sound at the driver's ear location for door closing operation. Main force was given on the finding of actual excitation applied or transferred during the door closing test. Test FRF and simulation FRF for the concentrated impact loads are calculated. Both FRF are compared and correlated. With reference to correlated simulation FRF results and using the inverse matrix method, the actual excitation load has been predicated. Lastly, using predicated excitation loads and, using the boundary element method (BEM), sound level is calculated at the driver's ear location. Sound, SPL at driver ear location of BEM and Test have better consistency (Fig. 8). The same can be used for other door closing sound evaluations.

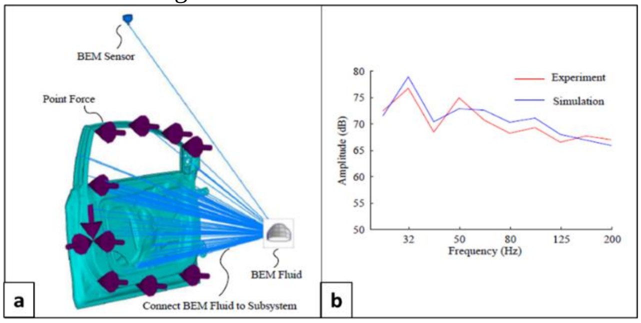

Fig. 8. (a) BEM simulation and (b) SPL Comparison Curve of Test and Simulation [4]

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

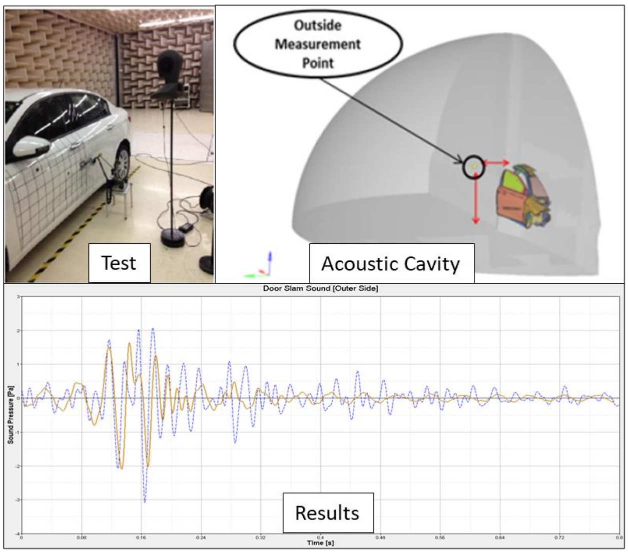

Fig. 9. (a) BEM simulation and (b) SPL Comparison Curve of Test and Simulation [5]

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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. Recorded data was evaluated by the jury/ participants based on a standard questionary prepared by researchers. The questionary main focus was to find auditory pleasantness in terms of attributes such as "Load", "Sharp", "Rough", "Clear", and "Satisfy". In the next stage 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 which had predicted subjective response of door opening noise. Based on this noise evolution study, they concluded that auditory loudness has a major 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 its different aspects. As its nature is transient and its effects are intangible on human beings. Researchers proposed the method to extract the psychoacoustic parameters of non-stationary vehicle door closing sound quality. This method was to evaluate the transient time-frequency parameters as objective parameters. Measured signal data was postprocessed by empirical mode decomposition (EMD) and intrinsic mode function (IMF) and analysed by spectrum analysis. On the basis of the human auditory frequency range, some of the IMF components are eliminated and effective 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).

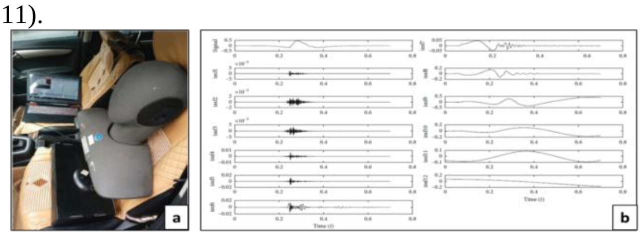
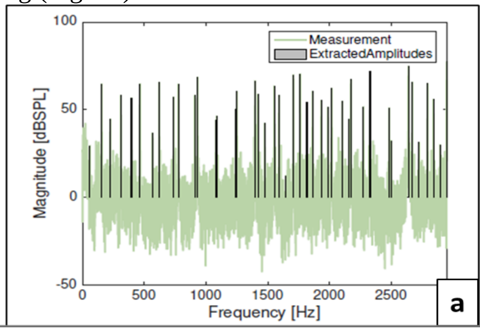


Fig. 11. (a) Noise Collection Set-up and (b) Each IMF Component of Sample S1 as a Example [7]

Mosquera-Sanchez et al [8], 2017: Inclusion of electric drive to make existing vehicle like hybrid electric vehicles (HEVs). They studied electrification and noise effects to the wider frequency band, mainly at higher frequencies. It presents the frame work for improvement of the sound quality of hybrid electric powertrain noise inside the vehicle compartment. This technique helps to reduce the amplitude of the tones at the optimization stage to get a better fit of auditory experience. Here's consideration is that psycho-acoustic parameters loudness, roughness, sharpness and tonality are most related to sound quality. The proposed framework verified with experimental results and it shows total success of >90%, which means proposed method is promising (Fig. 12).



Position	Loudness [sone]	Roughness [asper]	Sharpness [acum]	Tonality [SP]
1	38.88	0.66	1.29	0.96
2	50.00	0.68	1.42	0.90
3	49.60	0.64	1.59	0.97
4	42.73	0.79	1.21	0.96

b

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

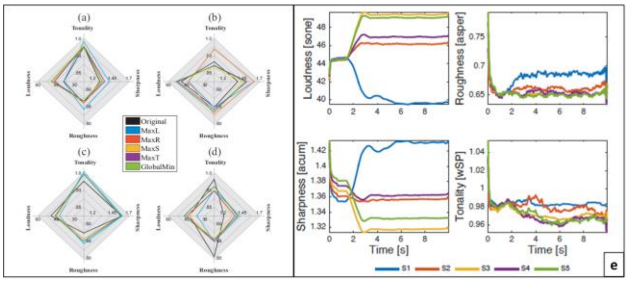


Fig. 13. (a) – (d) Radar Plots of the SQ Parameters and (e) Time-Domain SQ Parameters [8]

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 his own car and how it is 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 different vehicle (Compact, Sedan, and Luxury) has different expectations about interior sound quality based on their preferences. The hearing sensitivity and perception is based on their day-to-day experience under real usage. To do this, researcher has designed the questionary based on three different aspects or categories; first – demographic information, second – comfort level inside the cabin, and third – comfort level of loudness. A couple of example sounds were provided and asked to come up with a judgment about the sound/ data. In this survey a total of 42 participants (30 male and 12 female) were there. Sound quality response from this survey of 42 participant owners was that 80 % of owners feel comfortable with their own vehicle interior sound quality in terms of loudness and sharpness (Fig. 14). Results show a clear bias indication based on their driving experience.

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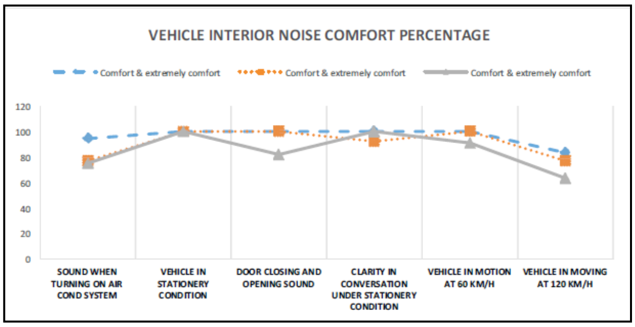

Fig. 14. Vehicle Interior Noise Comfort Percentage by Car Type under Different Conditions [9]

Zutong Duan et al [10][34], 2015: These researchers used Back Propagation Neural Network for Sound Quality Prediction (BPNN-SQP). They have taken full vehicle interior noise as an example source with four different operating conditions. Noises from operating conditions of vehicle Idling, Constant speed operation, vehicle accelerated condition and vehicle speed braking. Annoyance values of interior noises generated from the above-mentioned operation are fed into the BPNN-SQP model and output calculated in the form of annoyance values in terms 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 out respectively. Test results of the same operating conditions were correlated with output of BPNN-SQP (Fig. 15). Predicted annoyance results show accuracy of 95.57%. It indicates that the BPNN-SQP model may be used to evaluate the noise annoyance of different operating conditions and design evaluation.

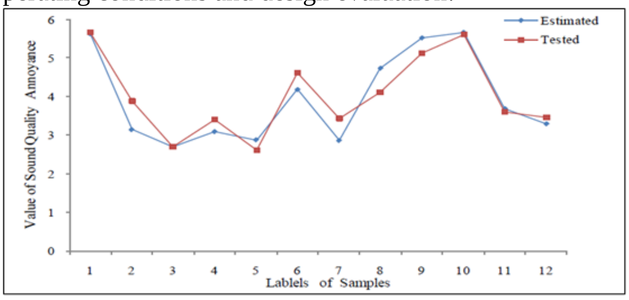

Fig. 15. Comparison of BPNN-SQP Estimated and Test Tesults [10]

Zongcai Liu et al [11], 2015: These researchers worked on train doors closing effect on sound quality. Because of the short closing time with high pressure. There were multiple sharp crests at low frequencies and the sound range was 50 Hz to 3000 Hz. Sound objective assessment was done with psychoacoustic sound quality parameters such as A-weighted sound pressure level, loudness, sharpness, roughness, and fluctuation which represent the people feeling about the sound. Different door sounds were evaluated and there was a discrepancy between the actual feelings about sound and the A-weighted sound pressure level, but loudness and roughness prediction were closed to subjective feeling. Going ahead, specific loudness was calculated and which effectively represents ingredient frequency of the sound. The specific loudness curve shown (Fig. 16) from 0 to 3 bark value is high for door no-1 and door no-4 and aligned with the door closing instant pressure.

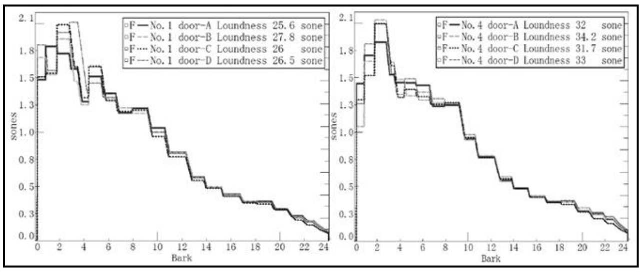

Fig. 16. Specific Loudness Curve of Door No.1 and Door No.2 Sound [11]

Hyeonho JO et al [12], 2014: 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 sound source study, it was concluded that door latch sound was generated by air-borne noise and not the effect of the noise path. The developed index was used as a tool for the optimization of door latch sound quality.

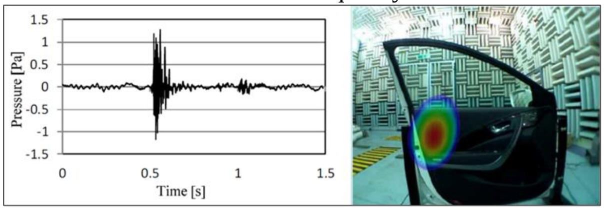

Fig. 17. Door Latch Opening Sound Spectrum and Visualisation [12]

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

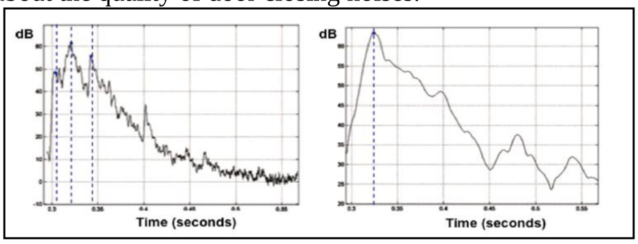

Fig. 18. Contribution in Door Noise from (a) Lock and (b) Door Closure [13]

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

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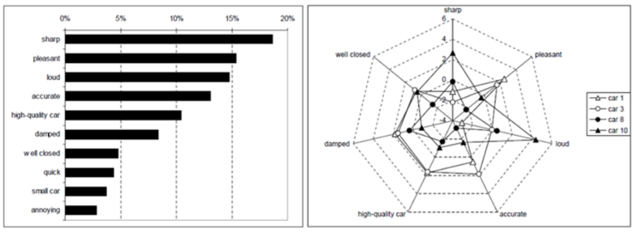

Fig. 19. Sound Evaluation Parameters [14]

G. Volandri 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 taken out in real time-function (Fig. 20) and compared with generic threshold values. Apart from tests, researcher have mentioned general definitions of psychoacoustic parameters of sound quality such as loudness, sharpness, roughness, fluctuation strength and kurtosis. The same time test conditions were simulated digitally and concluded that door panels and masking were having more effect on acoustic parameters. Finally mentioned, digital simulation and jury test are also equally important to conform to the behavioural significance of power window sound quality assessment.

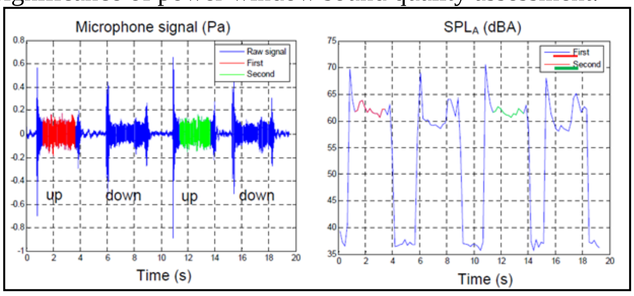

Fig. 20. Real Time Pressure and SPL [15]

M. Ercan Altinsoy [16][33], 2010: 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 reach the conclusion of this work, psychoacoustical tests were conducted using binaural head recording of both conditions of 12 vehicles of different brands. Recorded sounds are presented to the jury and asked to describe these sounds as a subjective test (Fig. 21). Both conditions results are evaluated sequentially and test experiments give hints of multiple events.

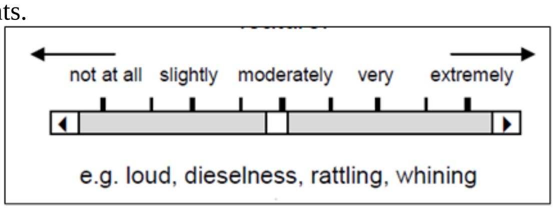

Fig. 21. Verbal Assessment Interface [16]

Gabriella Cerrato et al [17], 2009: Gabriella and team described basics related to the sound quality with examples. 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 the period and need to be reviewed and modified to account the current requirements.

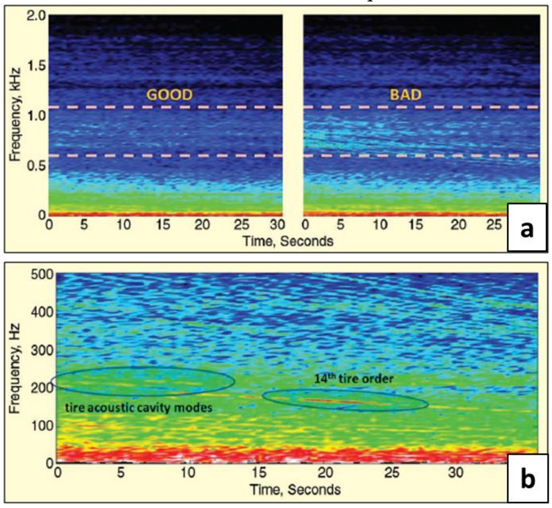

Fig. 22. Examples of (a) Good and Bad Road Noise Quality, (b) Poor Sound Quality Due to Low Frequency Tire Noise [17]

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 same but affects because of subjective annoyance value, levels and reach factor (Fig. 23). In the case of a time varying loudness function such as Jackhammer, the calculation should be done with use of DIN 45631/A1 (2008).

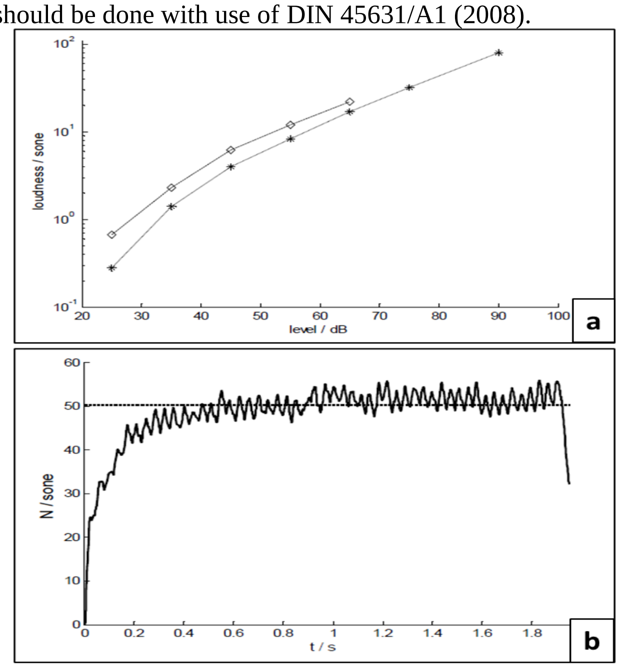

Fig. 23. Loudness of (a) Pink Noise as a Function of its Overall Level, (b) Jackhammer Noise as a Time Function [18]

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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, summarising the objective parameters and metrics used for accessories sound quality assessment. Briefed 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.

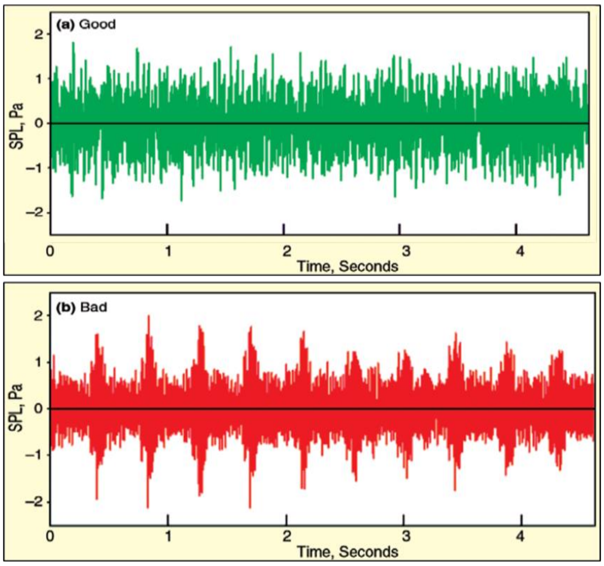

Fig. 24. Sound Pressure of Good and Bad Seat Adjuster in Time Domain [19]

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

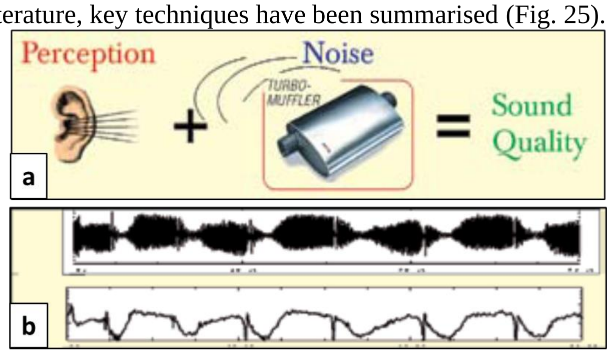

Fig. 25. (a) Ingredients of Sound Quality, and (b) Steering Wheel Vibrations (Time History and RMS Envelope) [20]

Fastl Hugo et al [21], 2007: Psychoacoustic parameter loudness was used to verify the noise reduction because of sound absorbing road surface. In this study, pass-by-noise/ loudness of the car was an estimated using procedure of ISO 10844. Sounds of five different (ISO, A1, A2, and A3 of different absorbing surfaces and B, a conventical non-absorbing surface) road surfaces effects were measured and evaluated in term of loudness and sharpness and compared with prediction (Fig. 26). Finally, the prediction of this study is that subjective evaluations and measured percentile loudness N5 have good agreement.

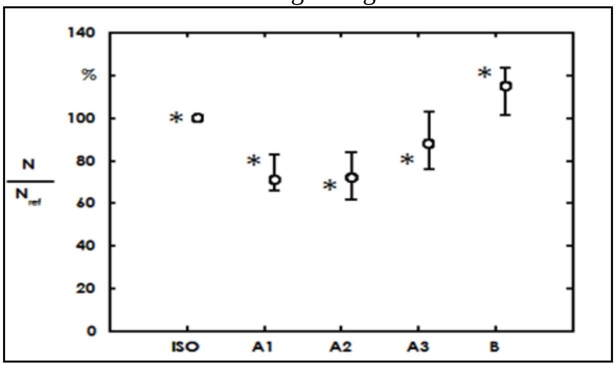

Fig. 26. Psychoacoustic Experiments (Circles) and Physically Measured Values of Percentile Loudness N5 (stars) [21]

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 acoustic head and the same sounds were heard by ten-ten, German and Japanese participants of 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 by semantic differential (Fig. 27). Culturally, different groups, of German and Japanese experts' pleasant impression results have good agreement of the car door sound quality.

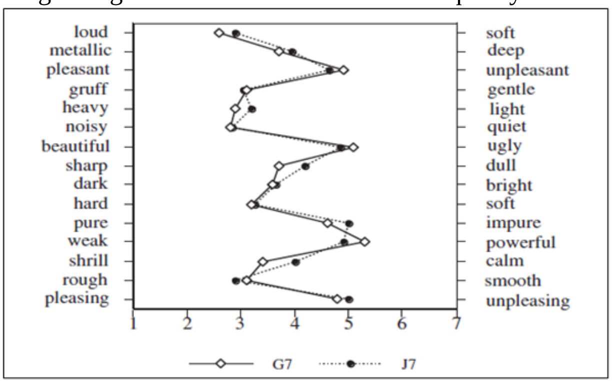

Fig. 27. Results of Best Correlated Sound Profile [22]

J K Lee et al [23], 2005: Car interior noise was tested and sound quality, psychoacoustics 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 by subjective method by 17 test engineers and rated their perception on the scale of 0 – 10.

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Outputs in terms of psychoacoustic parameters of the objective and subjective test were correlated. Most critical parameters were derived and a multi-factor regression equation (Fig. 28) was established for sound quality. Output sound quality indexes were compared with previous established indexes and well matched with human hearing prediction.

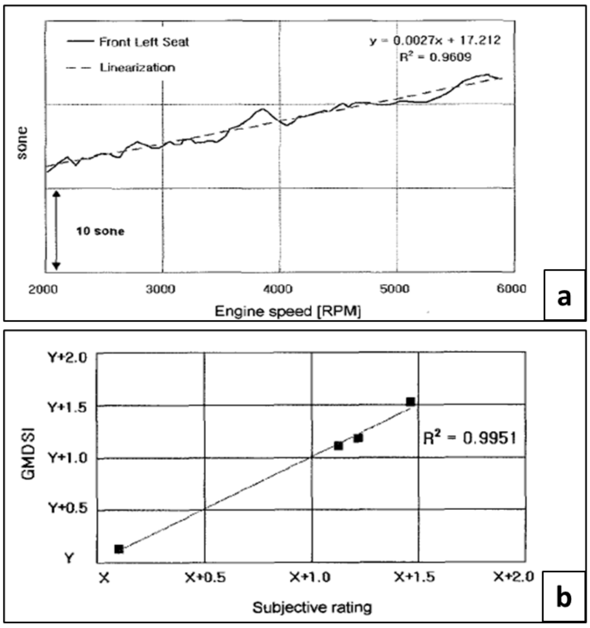

Fig. 28. (a) Level of Zwicker's Loudness and (b) Correlation of Subjective Evaluation for Wide-Open Throttle [23]

Anders Skold et al [24], 2005: Researchers work on the vibration of steering and seat for engine idle and car passing bride joint. Vibrational/ Stimuli were measured to find influence on sound quality. Measured vibration data was modified and presented to 44 jury members. Jury results show a strong connection of vibration with sound perceptions under steady state and transient conditions (Fig. 29).

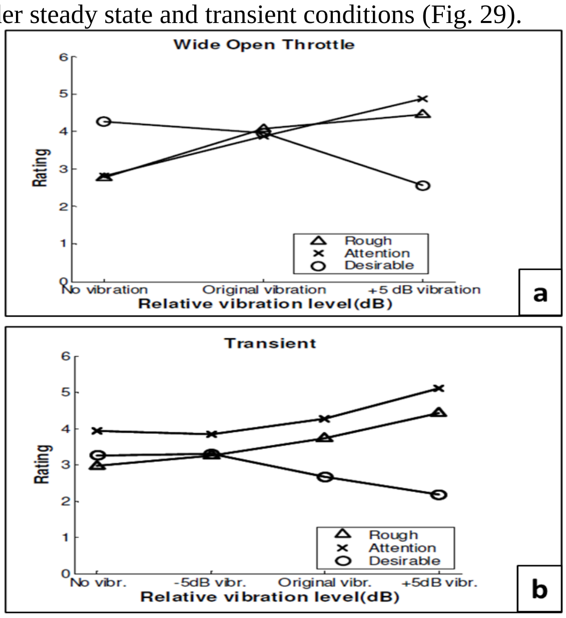

Fig. 29. (a) Rating for the WOT and (b) Transient Stimuli based on Three Adjective [24]

Martin Pflueger et al [25], 2001: Martin and team explained about the new software developed by AVL. The AVL VOICE software developed to assess the passenger vehicle interior noise in perception of sound quality (Fig. 30). Mainly, this software has the capability to measure / predict human feelings in objective form. This development has been done under the head 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 the sound quality in the objective term.

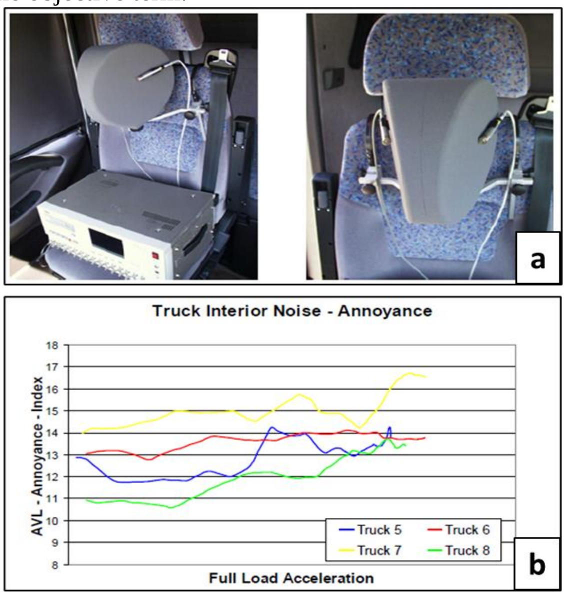

Fig. 30. (a) AVL Artificial Head, (b) Annoyance [25]

Patric Susini et al [26][32], 1999: A study revealed the approaches to improve sound quality considering multi-dimensional acoustic parameters which address the 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 feedbacks for all the samples that were listed and had evaluated. Feedbacks were correlated with perceptual dimensions which strongly agree. It represents the multi-dimensional sound samples and predicts close relation between perceptual and acoustic properties. It also defines properties of certain sounds which effect perceptual and comparison feeling.

Marek MORAVEC [27], 2019: Paper describes the psychoacoustic parameters and equipment – binaural used for evaluation of acoustic parameters. Also, talked about the general procedure of the sound quality evaluation process by measurement (objective method) and jury test (subjective method). Sound quality parameters related to the electronic home appliances and their definitions. Finally, it concludes that customer expectations can be more closely addressed by feedback given by human ear.

Tomasz Letowski [28], 2016: Tomasz, worked on sound quality parameters such as loudness, pitch, timbre, duration and spacious to define as well as describe them.

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All these parameters were compared with each other's. After then, types of sound quality have been described and finally tried to summaries the sound and sound quality images or characteristics in terms of two sound sources. All these aspects were combined in a sound assessment system – MURAL. The future success of this system is based on alignment and upgradation of current requirements.

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, for noise sound pressure, DIN 45631/A1 provides a method for time-varying sound calculations. ANSI S1.11 and IEC 61620 specify one-third octave band filtering. Using the above standards, the steering column electronic locking and un-locking noise loudness index were evaluated and the procedure has been laid down.

Klaus Genuit [30], 2004: Klaus, put all general information about the sound quality. Starting with meaning, definition and listing of influencing factors: physical sound feeling, psychoacoustic perception and psychological evaluation. Sound quality is a multi-dimensional phenomenon and should be dealt with in all aspects. To address this artificial head with multi-channel helps analysts to do effective evaluation of the noise data. Introduction about the subjective feelings and judgmental opinions are important to convert the sound quality in practical solutions.

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

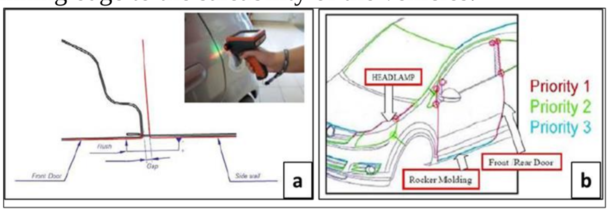

Fig. 31. (a) Gap and Flush Measurement, (b) Tolerance Management Priority Areas [31]

IV. SOUND QUALITY RESULT AND DISCUSSION

Most of the researchers worked on the car door sound quality simulation and correlation of objective and subjective parameters. All the researchers did the measurement of objective parameters in terms of sound and subjective parameters were taken based on the jury feedback. After the jury feedback, the same parameters were correlated with output of the developed virtual model or multi-parameter regression model.

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

Some of the papers are describing the sound quality parameters, definitions, characteristics, tentative frequency range and how it can be measured and evaluated.

It is good that maximum work or results has been correlated either by virtual tools or the actual jury test.

V. CONCLUSION

The door is one of the main structural noise sources in the car. Its noise behaviour is transient and short duration, so it has many variations to be addressed to improve the sound quality. Statistical analysis conceives that Sound Pressure (SPL), loudness, sharpness, roughness, fluctuation strength and tonality of noise are the main parameters to be worked on to achieve better sound quality. All mentioned parameters are addressing the sound quality but need to find the relation between each-others and need to find out, what is relation between these parameters and frequency or frequency band. These relations may help to address the sound quality issues and will help for deep study.

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DECLARATION STATEMENT

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ABBREVIATIONS

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

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CAE – Computer Added 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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