Hara et al., 2017

Volume 3 Issue 1, pp. 235-251

Date of Publication: 17th May, 2017

DOI- https://dx.doi.org/10.20319/mijst.2017.s31.235251

This paper can be cited as: Hara, D., Yağcı, A., Gürarda, A., & Erol, H., (2017). Investigation of Customer Perception of Vehicle Door Closing Sound Quality. MATTER: International Journal of Science and Technology, 3(1), 235-251.

INVESTIGATION OF CUSTOMER PERCEPTION OF VEHICLE DOOR CLOSING SOUND QUALITY

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Abstract

The perception of vehicle door closing quality is one of the most important criteria that a customer pays attention while buying a vehicle in a sales gallery. The quality perception gives a customer a clue about the general quality of the vehicle. A high quality closing sound of a vehicle door, has a potential of increasing admiration and attractiveness of the vehicle and sales volume of it. However, the quality perception has been a parameter that isn't calculated, measured or evaluated in the design phase yet. Within this study, closing sounds and physical and acoustical parameters of the doors of a group of B and C segment vehicles are investigated and compared *by handling some NVH and bench tests and jury evaluations. With the help of these studies, acoustical and thus physical design parameters of a door that has high quality closing sound will be determined and will show the path to design doors that has better door closing sound quality in the further vehicle projects.*

Keywords

Door Closing Sound, Door Slam Noise, Acoustical Performance, Customer Perception, Psychoacoustics

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1. Introduction

The vehicle door closing sound has a great effect on the customer perception about the manufacturing quality and luxury level of a vehicle. The customers can be attracted by sound when they are closing the door of a vehicle that they intend to buy. And if they don't like that sound, they may have a bad impression about the whole vehicle regardless of its general quality. Nowadays, in a competitive car sales market, vehicle manufacturing companies started to think that they should improve not only cost but also the general quality impression on the customers.

However, the quality of door closing sound is a very subjective quality that every customer has a different quality definition. Even most of the customers cannot define the sound they want to hear.

Several studies has been done related to this issue. Kumar et al. (2013) has studied door closing sound by comparing the doors with and without some modification by jury evaluation. In a study of Nunes et al. (2008), several vehicle door closing sound from the same model have been evaluated by jury and the anomaly has been pointed out on the car that has worst quality door closing sound. In a study of Champagne and Amman (1995), also a jury evaluation of opening and closing sound of several closure parts has been performed and the effects of sound parameters on sound quality are investigated. Besides, the reasons of sound parameters have been investigated in the study of Petniunas et al. (1999).

In this study, it is aimed to define the high quality door closing sound of B and C segment cars by the acoustical sound parameters and sound color maps. Furthermore, it is aimed to understand why a vehicle door has a low or high quality closing sound. These will enable the door designer and acoustical engineer to define a standard in order to have an objective quality index. With this standard, the high quality door closing sound will be guaranteed in the further vehicle projects regardless of subjective customer perception.

For this study, seven different cars were selected with their well-known high quality, mid-level quality or economic class perceptions. Their door closing sound data were collected by acoustical measurements as pointed in related test standards of the company. A jury evaluation was done to understand the customer perception without seeing the vehicles in order to eliminate the model, brand and company effects. Some NVH and body bench tests were done to define the high or low quality closing sound and understand its reasons by comparison.

2. Method to Obtain Door Closing Sound Parameters

There are a lot of sound parameters used in various applications but in this study the focus is on the door closing sound. The most common sound parameters used in door closing sound evaluation are loudness (in unit: Sone) and sharpness (in unit: Acum) of a sound. But they are not sufficient alone, so, sound pressure level (in unit: Pa), decay time (in unit: s), multiple impacts, roughness and wavelet plots (in unit: Hz/s) should also be considered for a better evaluation (Champagne and Amman, 1995) (Hamilton, 1999). These sound measurements and data collection must be done in a noise-isolated media such as anechoic or semi-anechoic chambers like shown in Figure 1.

Figure 1: *Semi-anechoic chamber*

Binaural sound measurements were conducted according to Fiat Chrysler Automobiles (FCA) norms using an Artificial Head Measurement System (HMS III Aachen Head) in a position facing the door from outside the vehicle. The height (1.65 m) and the distance (1 m) simulate a person closing the door. An elastic rope was arranged inside the vehicle cabin to slam the door opened from the outside at the exact speed of 1.2 m/s as shown in Figure 2. The speed was measured and confirmed using a JOFAVelpor speed measurement test setup.

Figure 2: *Test method of measuring door closing sound*

The door-closing event happens in a very short time. The duration is within a fraction of a second. An envelope of 0.8 second is analyzed for calculation of the sound quality metrics as seen in Figure 3.

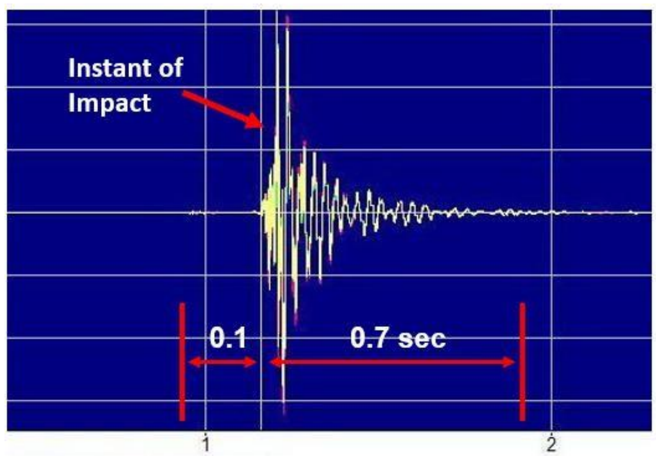


Figure 3: *Typical time signal measured during a door-slam*

3. Jury Evaluations

The door closing sounds of 7 cars were measured in this way and a jury evaluation was performed in order to represent the customers by making them listen to the sounds with headphones in a noise-isolated room as seen in Figure 4. The reason of this evaluation method is to eliminate the influence of trademarks and models on the customers' eyes. The brand of the car whose door slam sound being listened to was kept secret. The jury were selected from company employees as 53 members and they were asked to evaluate on paired comparison (7 vehicles: 21 pairs) and give points out of 10. After the evaluation of jury members, the answers were combined into one definite solution.

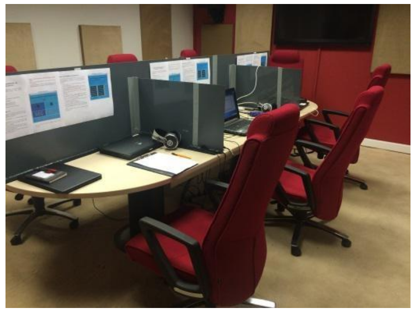
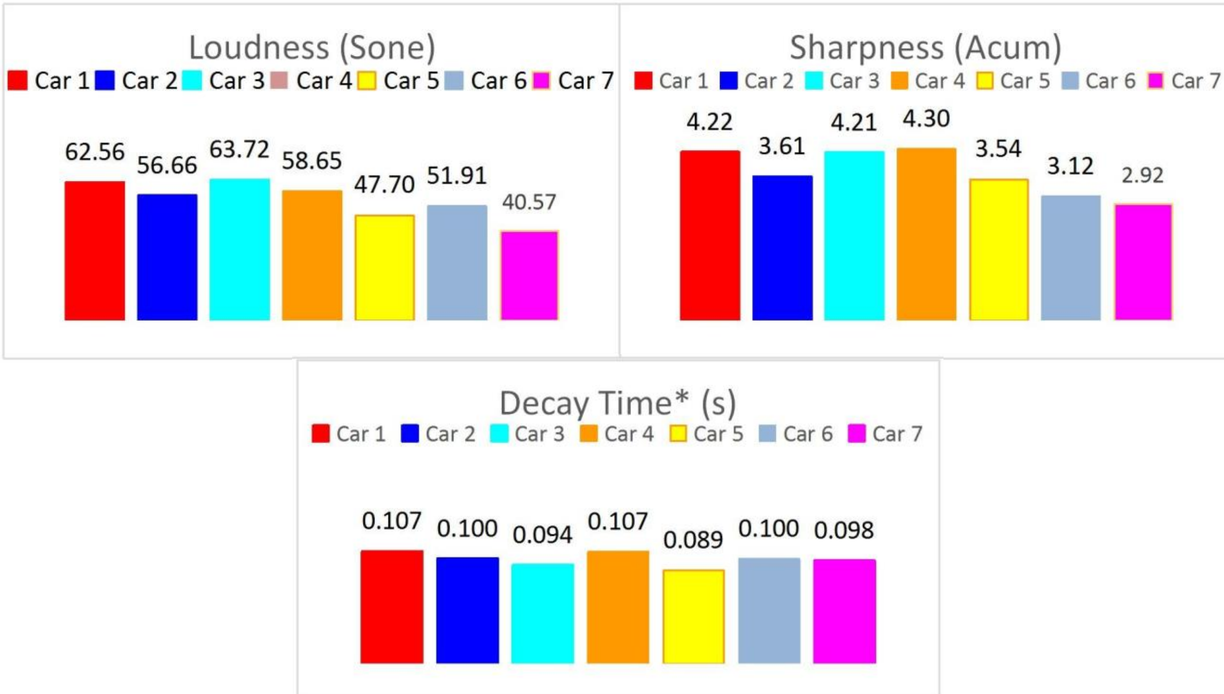


Figure 4: *Jury evaluation room*

Paired comparison method resulted as Car 5 > Car 3 ≈ Car 7 > Car 6 > Car 2 > Car 4 > Car 1 as Car 5 has the best and Car 1 has the worst door closing sound. And for grading, Car 1 has 3.7 points, Car 2 has 5.87 points, Car 3 has 6.19 points, Car 4 has 5.26 points, Car 5 has 7.33 points, Car 6 has 6.09 points and Car 7 has 6.25 points out of 10. Therefore the combined result of jury evaluation can be determined as: Car 5 > Car 3 > Car 7 > Car 6 > Car 2 > Car 4 > Car 1.

3. NVH Tests

Because of the privacy, the names of the cars will not be given in this paper. They will be called as Car 1 to 7 for the ease of designation. Both front and rear doors were studied but, only the results front left doors will be presented in this paper. The results of sound parameters that were analyzed by HEAD Artemis software are shown in Figure 5 and 6.



** Defined as the time interval in which the loudness value remains over 25 sone*

Figure 5: *Loudness, sharpness and decay time results of door closing sounds*

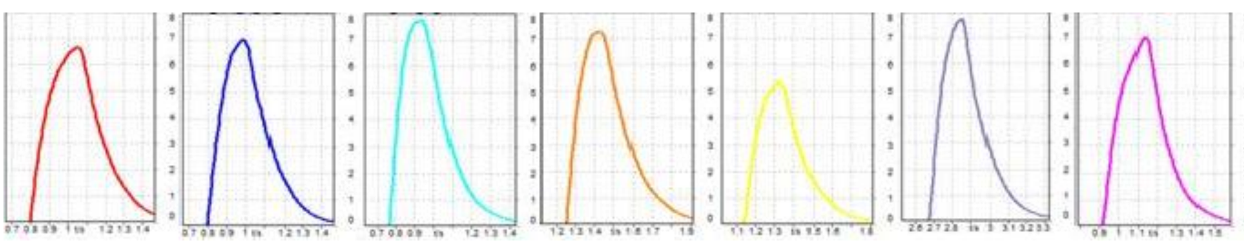


Figure 6: *Roughness results of door closing (Car 1 → Car 7)*

With these results, it is easily seen that the most liked sounds (Car 5, Car 7 and Car 6) have low loudness, sharpness, decay time and roughness values and the least liked sounds don't (Car 1, Car 2 and Car 4). So, it can possibly be said that these parameters have a negative effect on the sound quality and they also prove the results of (Champagne & Amman, 1995). Car 3 has incompatible results with these rules. The wavelet plots prepared by Artemis software can supply additional information to analyze this issue as shown in Figure 7.

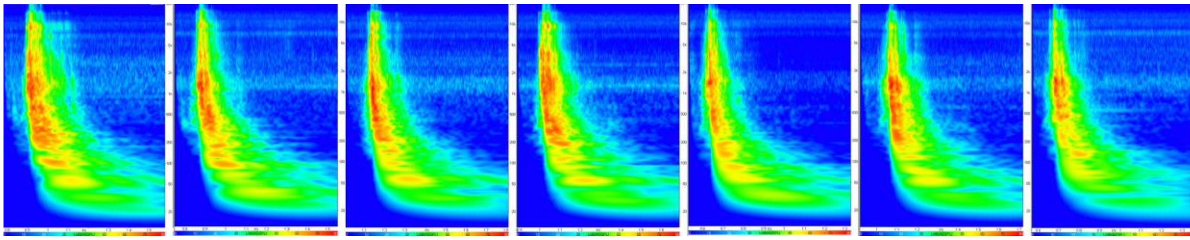


Figure 7: *Wavelet plot results of door closing sounds (Car 1 → Car 7)*

When the wavelet color maps are compared, especially for the Car 5 and Car 1 (Figure 8), the preferred sound has a shorter impact region, has a low frequency content giving a perception close to 'tonal' (not split to different tones), has a minimized high frequency content, has a minimized maximum amplitude (portions in red) and is free of rattle-like contributions.

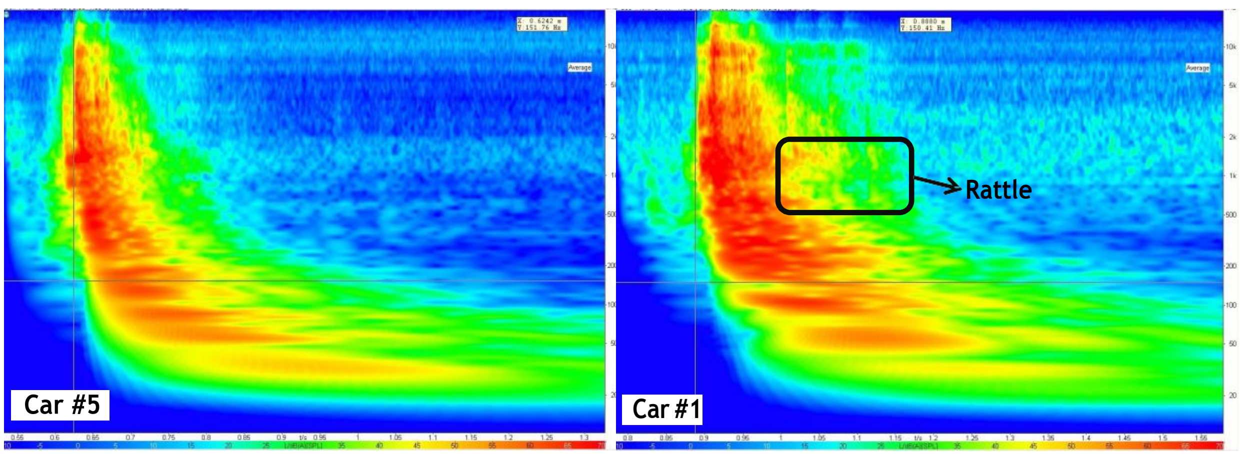


Figure 8: *Wavelets of Car5 and Car1 with colors re-scaled to highlight the differences*

The loudness and sharpness is related to the outer panel rigidity (Zhang & Young, 2005). In order to understand the effect of outer panel rigidity on loudness and sharpness, the vibrations on the door outer panels are also recorded at the same time with door closing sound measurements a high speed camera. On the recordings, the zones with high, medium and low vibrations are shown in red, orange and yellow circles respectively. It is seen in Figure 9 that, the front portions of lower zones are under high vibrations during the closing for most of these cars. It is believed that the weakest zone is that portion of the door outer panel.

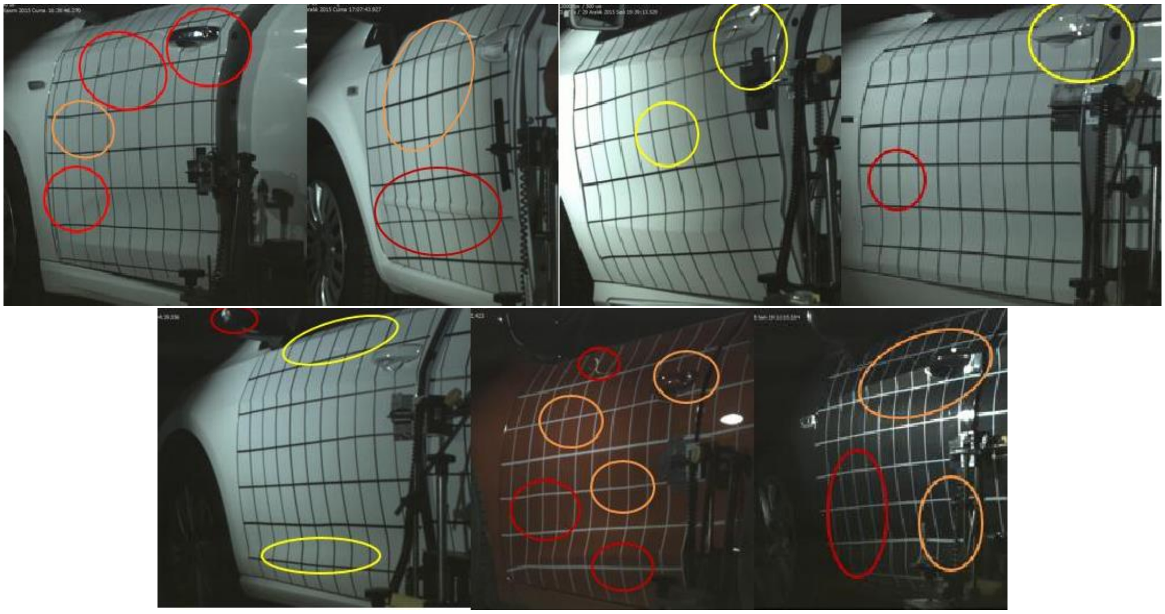


Figure 9: *The high speed camera records of door closing (Car 1 → Car 7)*

To investigate the outer panel vibrations, 20 single-axis accelerometers (B&K 4507 B004) were used to collect vibrational data during door slam as a separate measurement session. The accelerometers were positioned as possible as homogeneously over the outer door panel. Operational Modal Analysis (OMA) and Operational Deflection Shapes (ODS) were utilized. Siemens LMS Scadas front end was used for vibrational data acquisition and related structural analysis modules of Siemens LMS Test. Lab software were used for OMA and ODS.

The results of binaural acoustic measurements and OMA for most and least liked cars (Car 5 and Car 1, respectively) by the jury can be seen in Figures 10 and 11. Figure 10 shows the frequency spectrum of the binaural acoustic data while Figure 11 presents the operational FRF sum of the 20 points on the outer panel for the low frequency region of 20-160 Hz.

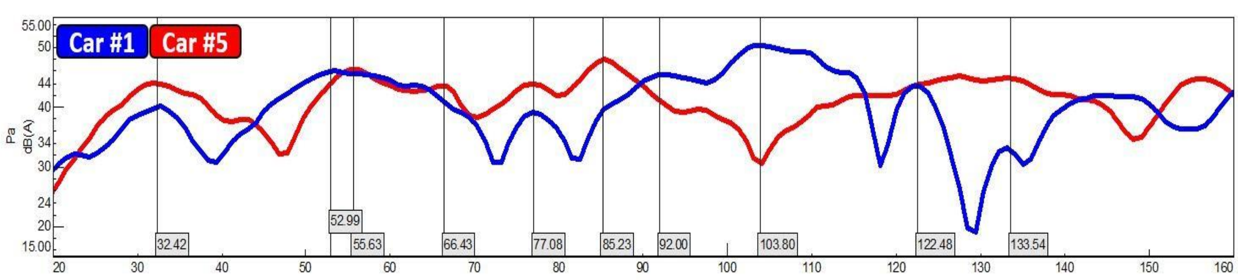


Figure 10: *Comparison of binaural acoustic measurement results for Car 1 and Car 5*

The first two peaks on the acoustic curves are around 32 Hz and 55 Hz for both cars, with the amplitude at 32 Hz higher for the Car 5. These two frequencies can be traced on OMA graphs. The reason that not all the acoustic peaks are correspondingly visible on modal analysis graphs is possibly because the rest of the acoustic peaks are resulted from the resonant frequencies of the components on door structure other than the outer panel. This explanation is also supported by the OMA graphs in Figure 11. Although there are no distinct peaks for the Car 5, its curve has a lower level than Car 1 between 40 and 160 Hz. This means that the outer panel vibrations are lower for the Car 5, however, these vibrations are not the only responsible contributors to the low-frequency acoustic radiation.

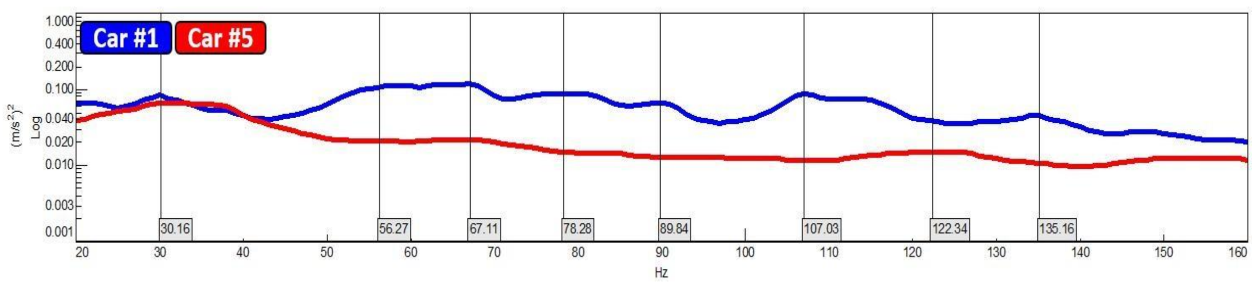


Figure 11: *Comparison of OMA results for Car 1 and Car 5*

Figure 12 and Figure 13 demonstrate the 28-32 Hz and 53-57 Hz operational deflection shapes of the Car 1 and Car 5, respectively. From these figures, it can be seen that the vibration pattern of the outer panel of the Car 1 has a much more ‘local’ characteristic compared to that of Car 5. This may be defined as a flutter-type of motion, whereas the outer panel of Car 5 vibrates more globally. This finding is in parallel with visual perception received from the high-speed camera recordings of these two cars. It can be concluded that a ‘tonal-like’ low frequency content, which is one of the preferable door-closing sound characteristics, is achieved by a more ‘global’ outer panel vibration pattern.

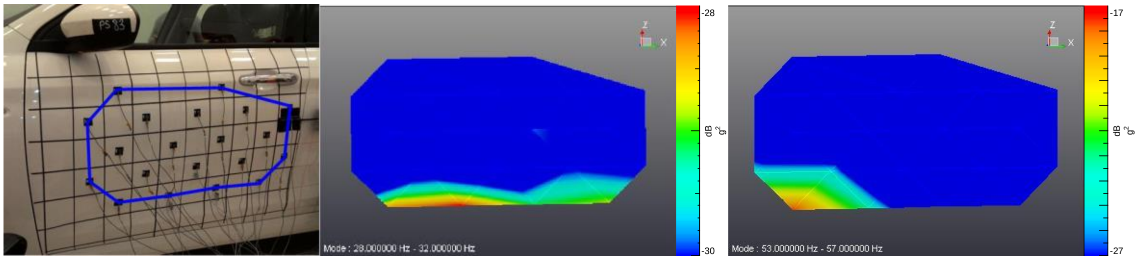


Figure 12: *28-32 Hz and 53-57 Hz Operational Deflection Shapes (ODS) for Car 1*

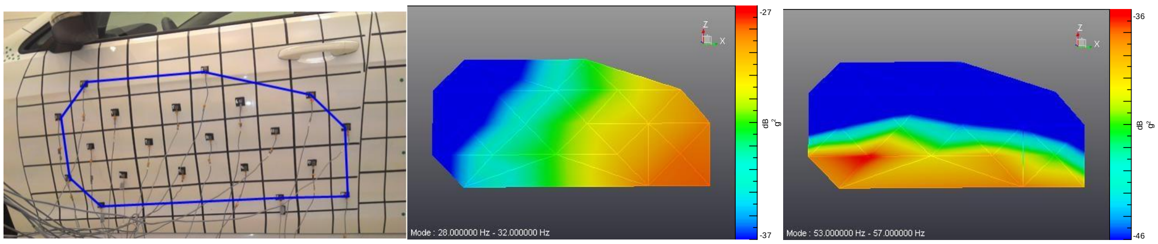


Figure 13: *28-32 Hz and 53-57 Hz Operational Deflection Shapes (ODS) for Car 5*

3. Bench Tests and Designs of Doors

Only NVH tests are not sufficient to understand the reason of the main factors that influence the door closing sound. In this section, some bench tests were performed to obtain the lateral, vertical and panel rigidities of the doors, door closing efforts and door closing energies in order to understand their effect on the jury's like. These parameters were obtained with bench tests which are determined by the company test standards and methods. Besides, panel rigidity tests will help us to deeply understand the results of the records of high speed camera and ODS's.

The aim of the panel rigidity test is to simulate the situation of leaning and wiping of a person. Upper part of green line is leaning zone and lower part is wiping zone and their initial stiffness targets are 33 N/mm and 22 N/mm respectively. The door was attached tightly to the bench and some regular lines were drawn onto the panel so that these lines have a specific distance to style curves and edges. A force was applied as increasing and then decreasing manner and the displacements and force on specific points were measured. The results can be seen in Figure 14 (The result of Car 2 only shown as no visible deformation is seen).

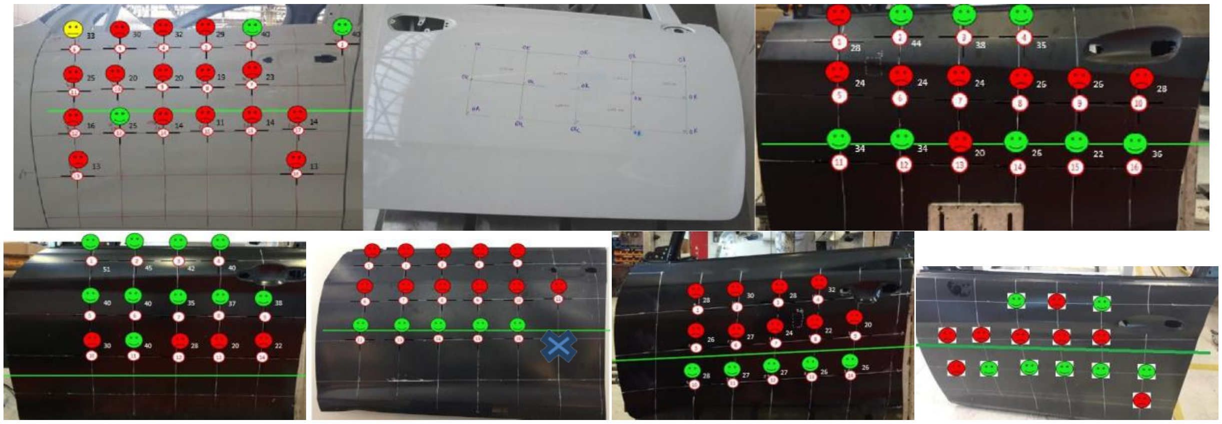


Figure 14: *Panel rigidity tests results (Car 1 → Car 7)*

It can be seen that, for Car 1, has a weak (low rigidity) points where the vibrations occur in the records of high speed camera. Plus, the ODS's support these rigidity levels. The reason of this low rigidity in that area is why only outer panel is not supported from inside with a bar or anti-flutter applications. From this point of view, it can be said that loudness and sharpness of the door closing sound can be decreased by supporting that area thus a better quality door closing sound may be obtained.

By looking at the rigidity results of Car 4, this door has a very high rigidity. When we look inside its design in Figure 15, it is very well supported by crash bars and large anti-flutter material. Therefore, it also proves the high speed camera results for having very low vibrations on the outer panel. Nevertheless, closing sound of this door is not liked very much about the jury. So, the reason is thought to be decay time and some rattles inside the sound.

Figure 15: *Inner sights of designs of doors (Car 1 → Car 7) (Both inner and outer panels of Car 5 is shown)*

During the test of door of Car 5, the point where it is indicated with blue cross in Figure 14, a collapse has occurred because in the test door, anti-flutter applications were missing where they supposed to be in Figure 15. By looking at the camera records and modal analyses, the crash bar and anti-flutter applications seem to be very supportive to the outer panel, because it has very low visible vibrations on that areas.

One other of the bench tests is vertical rigidity test. The aim of this test is to understand the performance of deflection under vertical loads and its influence on the quality of door closing sound. In this test, door was positioned in 25° and a force was applied from its latch area in the vertical direction and waited for some time to measure both temporary and permanent deflections as shown in Figure 16.

Figure 16: *Vertical rigidity tests of doors*

Due to results of this test, that are shown in Figure 17, it is possibly said that, the vertical rigidity has a good effect on door closing sound quality.

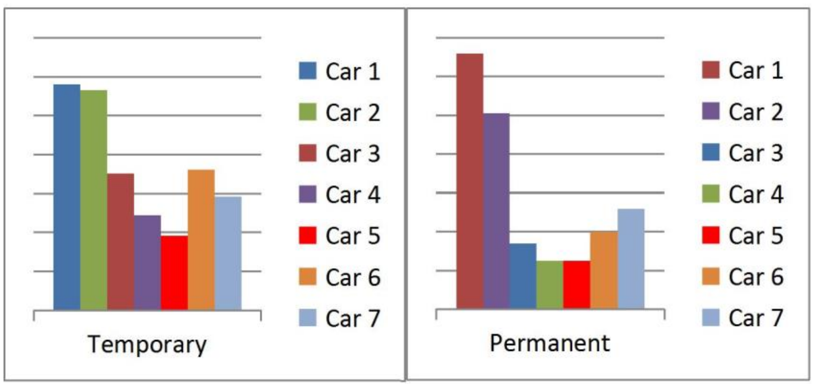


Figure 17: *Vertical rigidity tests results*

The aim of the next bench test, measuring lateral rigidities, is to understand the effect of the frame rigidity on the quality of door closing sound. Door was tightly attached on the bench and forces were applied separately on 3 points on the frame as shown in Figure 18 (for some cars, forces couldn't be applied to all three points). As in the vertical rigidity, it must be waited for some time to measure both temporary and permanent deflections.

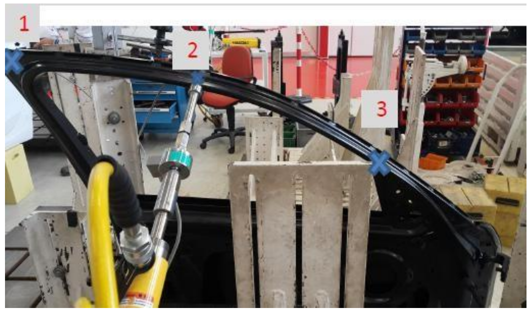


Figure 18: *Lateral rigidity tests*

By the test results, shown in Figure 19, a clear judgment cannot be developed on the effect of lateral rigidity on the door closing sound quality.

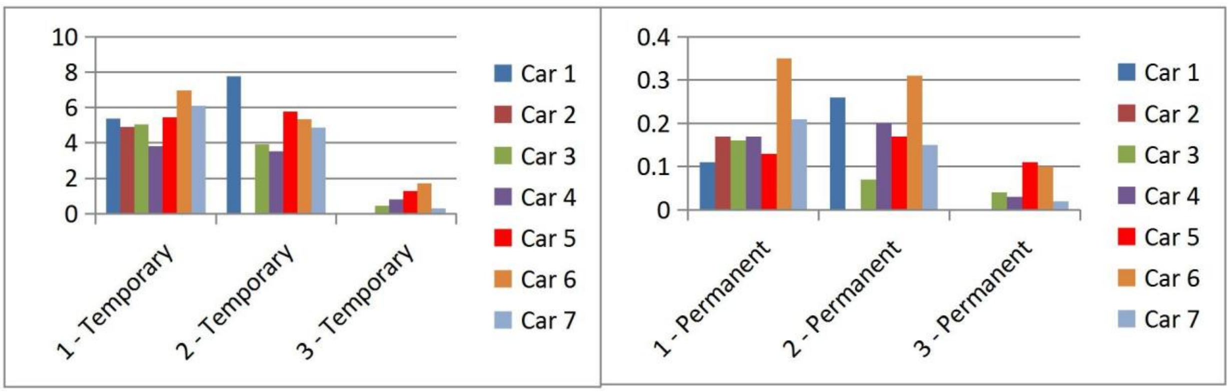


Figure 19: *Lateral rigidity tests*

The other bench test is door closing effort. It was performed to see the minimum force necessary to close the door and effect on door seals, bumpers and latches on the closing. It starts with the closing of the door until the first click is heard from the latch. After it, the door was pushed to be closed entirely and a dynamometer measures the closing effort as in Figure 20.

Figure 20: *Door closing effort tests*

By the test results, shown in Figure 21, a clear judgment cannot be developed on the effect of door closing effort on the door closing sound quality.

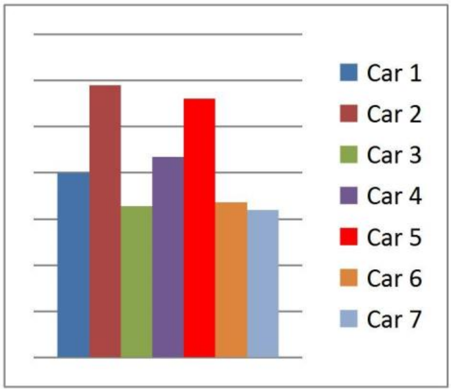


Figure 21: *Door closing effort test results*

The last bench test is door closing energy measuring in order to see the minimum energy necessary to close the door and effect on door seals, bumpers and latches on the closing. It is aimed to understand the effect of door closing energy on the door closing sound. In the test, a force was applied on the door as seen in Figure 22 and the energy was calculated with the device.

Figure 22: *Door closing energy tests*

The test results are shown in Figure 23. With these results, it cannot be developed a clear judgment on the effect of the door closing energy on the door closing sound quality.

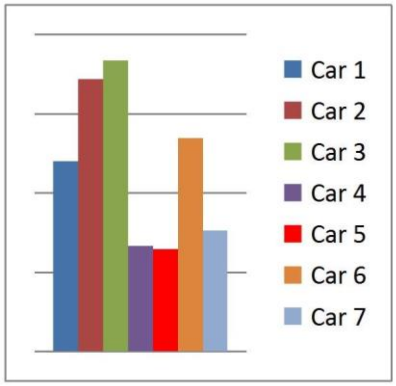


Figure 23: *Door closing energy test results*

4. Discussions and Conclusions

The customer perception of vehicle door closing sound is investigated through some NVH and bench tests. It is seen that the mostly used sound parameters such as loudness and sharpness is not sufficient to understand the sound quality. Some other parameters, such as roughness and decay time, may be needed. Also the wavelet plots provide some useful details. The vibrations of outer panel or other structural door components can be analyzed by OMA and ODS as well as by high speed camera recording. These recordings will provide useful information for the low frequency sound radiation during a door slam. For a deep investigation, the characteristics of the door structure affecting the closing sound are investigated through some bench tests and by visual and technical inspection of the different door designs.

As a result of this study, a preferred door closing sound should have:

- low loudness level and overall SPL
- low sharpness level, minimized high-frequency content
- low-frequency content perceived as one dominant tone, not split to different tones
- short impact time free of reverberations
- less rattle-like strange sounds giving rise to a ‘low quality’ perception

Within this study, it is also concluded that the door outer panel rigidity seems to be an important matter for panel vibrations. The high level vibrations zones should be detected and additional support mechanisms should be applied on that zone to eliminate the vibrations, thus loudness and sharpness. Furthermore, some engineering solutions must be developed to increase the vertical rigidity in order to have a better quality door closing sound. The lateral rigidity, door closing effort and energy is found to be ineffective on the improvement of vehicle door closing sound.

For future studies, some parts of the door or door system can be individually modified and tested to see how it is affecting the sound quality. By knowing individual part effects and know-how of this study, a design method can be developed to predict the closing sound not after the car is produced but in the design phase.

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