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Automotive Doors as Loudspeaker Enclosures

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ABSTRACT

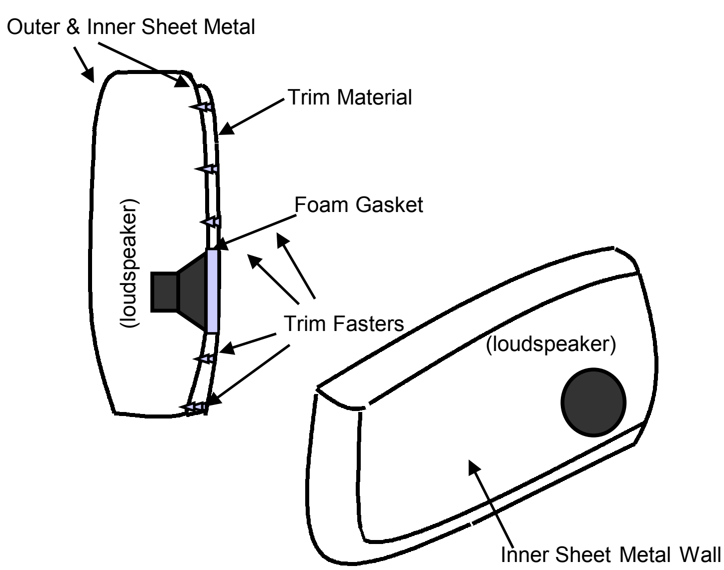
The results of a study of the quality of automotive doors as loudspeaker enclosures are presented. Electrical and acoustical measurements of several automotive doors are made and compared to linear box theory. Judgment criteria are considered for quantifying the doors as enclosures and relating that to the sound quality using roughness as one of the criterion.

0. Introduction

In automotive audio, the location of the door has traditionally been used as a loudspeaker enclosure. Trends in automotive manufacturing tend to be at odds with that. Lighter doors, with less and less inner sheet metal for mounting and enclosing loudspeakers, especially in smaller class vehicles, are contrary to the need to get more low frequency information from the door location. At the same time, the problem of packaging of subwoofer enclosures is becoming more and more difficult, making the need for getting more and more low frequency from woofers in doors even greater. With that in mind, we began an investigation into quantifying and qualifying automotive doors as loudspeaker enclosures. Impedance, distortion, and roughness measurements of several doors were used to compare with low frequency response performance and low frequency sound quality.

1. Overview of Automotive Doors

The interior volume of the doors used in this study ranged from 16 L to 65.5 L. These were doors from small coupes to large sedans and midsize sport utility vehicles. Eight individual doors are included in the results of the study. Two of the enclosures were chosen to be compared to rigged wall, “sealed” enclosures for the same shapes and volumes. There are many sources of volume variability and extraneous noise in automotive doors. Beside loudspeakers, automotive doors house window motors, windows, window tracks, side impact reinforcements, and door release bars. The trim panels hold switch panels, lighting, map pockets, door release mechanisms, and loudspeaker grills. All the doors in this study were roughly the same size, but the available interior volume varied. For instance, Door 6 (See Appendix 1for pictures and brief title descriptions of each of the eight doors) is the same size as Door 7, but only one quarter of the door volume was available for the loudspeaker. Another door, Door 2, had the entire door volume available to it, but less than a loudspeaker diameter away, there was a large opening in the sheet metal, effectively removing the front wall from the loudspeaker enclosure. All the other doors fall somewhere in between, and are typical of automotive doors. As we will see, the door sheet metal is rarely a sealed enclosure, leaving the interior volume open to the door's trim, with the trim sometimes becoming a vital part of the enclosure system. We will also see that the coupling of the inner door volume to the outer volume created by the door trim could be beneficial, if that can be done in way that is controlled enough not to excite the door trim to the point of creating extraneous noise. Typically the trim for automotive doors is attached using a variety of fasteners: metal clips, plastic "Christmas tree" designs, and pop-rivet type designs. These kind of attach methods can vary over time, or just in their initial manufacture, adding to the variability of door enclosure's performance. While plastic enclosures built to fit into the door interior would provide a more stable design, the use of the entire door volume would be prohibited. That volume would be replaced with the reduced volume of the plastic enclosure, reducing the useful volume for producing low frequencies. This is even more contrary than the design of the door itself to our desires as audio system designers and integrators. Therefore, we need to be able to qualify a door for its use as a loudspeaker enclosure.



Sketch 1. Automotive Loudspeaker and Door System Enclosure

2. Measurements

One of the initial designs of this study was to relate the door enclosure to typical box enclosures and qualify them against ideal box design parameters. Impedance data and frequency response measurements were made for the purpose of comparing to linear box theory. Distortion measurements were made to search for extraneous noise in the door enclosure system.

From Small [1], [2], [3], for closed and vented box designs, the linear box design small-signal parameters are resonance (F), mechanical Q (Q_m), electrical Q (Q_e), total system Q (Q_t), compliance ratio (α), and total system compliance as a volume (V_{AT}). For a vented box design, there is the added parameter of total enclosure loss (Q_L). For each of the doors and loudspeakers, impedance measurements were made (at 1vRMS) of the loudspeaker out of the door in free-air, with the loudspeaker back in the door, and then with the trim replaced on the door. The data was then transferred into a spreadsheet, where any analyses and graphs were made. One door (Door 7) had a set of impedance data which resembled that of a ported enclosure. For that set of data, it was treated like a ported enclosure for analysis, which led to calculating the value for Q_L.

Frequency response measurements (at 1W) were made for each of the doors. For these, the microphone was placed at a point that was 50 mm from the grill of the door trim, and kept at that point for the measurement without the trim. Distortion measurements were made for doors, with and without the trim, using the Boink measurement technique. [4] The microphone was set again at 50 mm from the grill of the door trim. The output of the door, with trim, was set to 85dBA with a pink noise source. Then the EIA426B CD with Boink test tracks was used as the source for the distortion measurements.

The measurement data is presented in Appendix 1. The Boink testing was measured for all the third-octave centers from 20Hz to 315Hz, but only a few of the frequencies of 31.5 Hz, 50Hz, 80Hz, and 125Hz were included here. It is enough to illustrate the point that the Boink test only provided odd harmonic distortion of the loudspeaker.

3. Door data analysis

Initial inspection of the impedance data for just the door without the trim in place [See Appendix 1] shows that none of the door enclosures behaves like a theoretical box and does not follow linear box theory. The same data with the door trim in place shows that the non-linear behavior is maintained and impedance at resonance has been reduced from the door without trim. That decrease at resonance would indicate, at the very least, a form of coupling to the trim with a potential increase in efficiency. Compliance ratios (α) were calculated for each door with and without trim. The results show values for α which are extremely low or in some cases negative. The data doesn't visually adhere to the linear model and the parameters aren't accurately provided either. Looking just at the impedance for the doors without trim, three different types emerge: Type I = shows minimal change from free air, Type II = skewing of the curve becoming asymptotic to the free air curves below resonance, and Type III = a complete resonance shift down in frequency. Linear box theory tells us that the resonance frequency and Q_t should increase. Those two things don't necessarily happen, but because we're applying non-linear data to a linear model, there isn't necessarily much meaning to the enclosure parameter values.

	Type I	Type II	Type III
	Sport Coupe (Dr 2)	Sm. Sedan (Dr 1)	Med SUV (Dr 4)
		Lg. Sedan (Dr 3)	Med SUV (Dr 5)
		Coupe (Dr 6)	
		Lg. Sedan (Dr 7)	
		Med SUV (Dr 8)	
Total	1	5	2

Table 1. Door (without trim) Impedance Type

The data for Door 7 with the trim off it was labeled a Type II because of the skewing of the impedance curve, but with the door trim on, it resembles a ported enclosure. (Type IV = Double Maxima similar to a ported enclosure). It has a value of Q_L = 7.8. With that value of Q_L, this enclosure system is poorly aligned. From Small [5], with a Q_L= 7, the Q_t of the enclosure should be down around 0.4 instead of being close to 1.0, which is the case for Door 7. This can lead to a frequency response that is poorly underdamped and has a poor transient response. For enclosure losses of 5 and above, there is a negligible power loss for QB3 type of alignments, but starts to effect C4 alignments. The loses and poor alignments in door enclosures can cause problems for the audio system designer to drive the enclosures below the loudspeaker passband and forces them to drive them above or at the second impedance maxima, which greatly compromises their ability to produce more low frequencies from the door. In this particular case (Door 7), the second maximum was at 67.8 Hz. The system designer found the enclosure unusable below 60 Hz, and set the highpass filter for that loudspeaker at 65 Hz.

Door	Imp Types (No Trim/Trim)	Freq. Response Change No Trim -> Trim
1	II / II	50 – 150 Hz, +3 dB
2	I / II	40 – 50 Hz, +2 dB
3	II / II	20 – 1k Hz, +5 dB
4	III / III	None
5	III / II	20 – 1k Hz, +4dB
6	II / II	50 – 150, +3 dB
7	II / IV	125 – 200, - 3 dB
8	II / III	20 – 600, + 3 dB

Table 2. No Trim / Trim Impedance Type & Frequency Response

For the Type III door impedances, where there is a complete resonance shift down, rather than a skewing or the theoretical shift up. There is some sort of mass loading occurring to create the increase in apparent moving mass. Door 4 is the best example of this. There is a resonance shift for the door and that resonance is maintained when the trim is on the door (Type III/III). It is not possible from this data to determine the exact cause of the resonance shift. The door enclosures are presumably lossy enclosures with less than rigid baffles, and that could contribute to the increase in apparent moving mass and lower resonance. That lossy characteristic is also a source of uncontrolled behavior until it can be understood and manipulated. The lowering of resonance can be an obvious benefit for improved low frequency output, but what unknown attributes it brings with it is cause for precaution.

An analysis of the frequency response data for the doors with and without trim is summarized in Table 2. In nearly every case, the addition of the door trim increased the low frequency output of the door enclosure system. Those door systems that are Type II impedance types (skewing of the curve becoming asymptotic to the no trim curves below resonance) with trim on always had some significant increase in low frequency SPL, especially if they were Type II / II. This meant that the trim was instrumental in increasing the low frequency output, whereas for the Type III / Type III or Type I / Type III, the door was governing it's behavior, not the trim.

Visual inspection of the Boink Data curves show that the measured distortion is the odd harmonics of the loudspeaker. The Boink test was not useful in the way we had hoped. We wanted it to highlight extraneous noise being generated by the door or trim, but instead it did a very good job measuring the quality of the loudspeakers used in these doors in and outside of their passbands.

4. Comparison of two known doors

Two doors were chosen to be compared to sealed-box versions of their door's volume. Door 2 was chosen because it seemed to be the worst at being an enclosure. That was based on its door impedance measure resembling a free air measurement (Type I / II) and by it being the worst sounding door of all those measured. Door 7 was chosen based primarily on it being one of the better sounding doors. Its impedance measurements (Type II / IV) were interesting as well, exhibiting pseudo-ported behavior. Door 4 would have been a good candidate also, because it was probably the best sounding door. But, the volume sizes of Door 2 and Door 7 were nearly identical (65.5 L) and served as the best and worst case of using that volume.

This comparison data is at the end of Appendix 1. Primarily the data serves to illustrate that neither of the doors is a sealed enclosure. This can be seen in the impedance plots, where the sealed box impedance exhibits linear behavior and the theoretical resonance shift up in frequency. And it can also be seen in the frequency response data. The sealed-box approximates a theoretical 4th order response in the low frequencies, and the door enclosures both look like 2nd order systems. For Door 2, adding the door trim reduces the low frequency output even more, by an additional 3 to 5 dB below 100Hz.

5. Additional Measurements

From the door data analysis above, there was an indication that there is an apparent mass loading of some of the doors. Given that, Klippel measurements were made for the loudspeakers in free air and inside the door to determine the apparent moving mass (M_{ms}) for both. [6] For doors with trim Type III, the apparent moving mass is not changing anymore than by +3%. For Type II / Type II enclosures the Mms apparent mass can increase by as much as +25%. Door 3 does just that. It has an M_{ms} change from 15 g. in free to 19 g. in the door. The skewing of the impedance curve for the type II's, could mean that there is higher coupling to the door in that instance. The phenomenon of resonance shifting completely (Type III / Type III), no longer staying asymptotic, is unexplained. It somehow seems uncoupled from the door. Keep in mind that M_{ms} is a parameter from a linear model, and we are trying to apply it to what certainly appears to be to some degree non-linear behavior.

In order to look for some measured correlation to the sound quality of the doors enclosures, two of the doors were also measured for roughness. Door 2 and Door 7 were used again for this analysis.

The roughness measurements were made at a microphone distance of 25 mm from the speaker grill and centered there. They were taken again at 0.612 m from the center of the door trim. The second position allowed for recordings with a better balance of speaker sounds and any door buzz noises. HEAD Acoustics ArtemiS software ver. 4.00.200 uses a roughness algorithm based on the method by Aures [7] and was used for the analysis. The measurements were made from 20 Hz to 20 kHz, but only data up to 8 kHz is presented. For Door 2 (2-ohm loudspeaker), voltages of 2, 4, and 8 Vrms were used, while for Door 7 (8-ohm loudspeaker), voltages of 4, 8, and 16 Vrms were used. This allowed for comparisons between the cars at equal power input levels.

From Terhardt [8], Aures [7], and Daniel and Weber [9], roughness is described as a hearing sensation that is caused by rapid fluctuations in the temporal envelope of a sound which gives the sound an unpleasant nasty fluttering or growling character. An increase in roughness corresponds to an increase in unpleasantness.

For roughness to occur, the envelope fluctuation frequencies need to be in the range of 20 to 300 Hz. The fluctuations are due to frequency components with spacing between 20 to 300 Hz occurring within a critical band. Most of the extraneous noises from speakers and car panels produce frequency components meeting these criteria – this is what we hear as objectionable. However, this is still a very subjective measure. No limits of acceptable roughness have been established. In general, a 1 asper difference is noticeable and therefore distracting. For speakers, the noises can be caused by a wide variety of phenomena such as suspension noise, spider and voice coil bottoming, voice coil rubs, screen buzzes, mounting buzzes, lead wire hitting, and improperly vented air volumes under the dust cap. In the door, the components mentioned before (windows, motors, tracks, side impact reinforcements, switch panels, lighting, map pockets, door release mechanisms, and grills.) can be excited acoustically or mechanically and produce disturbing buzzing or rattling noises. Air turbulence and air loading imbalances in the door enclosure system can also be sources of unpleasantness.

The roughness data is located in Appendix 2. The 25 mm mic. distance data is shown in Fig. 1 – 4. And the 0.610 m mic. distance data is shown in Fig. 5 – 8. This data was generated from recordings that could also be used for listening audits as well as the roughness calculations. The characterizations that are made based on this data are made after listening to those recordings and forming a correlation.

For the 25mm mic. distance data, the source of the roughness can be mostly attributed to the loudspeaker and any influences the door enclosure has on it. For Door 2 (Fig. 1), there is a dramatic growth in roughness when the voltage is increased from 4 to 8 V, adding a very nasty character to the 8 V recording for input frequencies below 120 Hz. This roughness was attributed to a slight voice coil rub when the loudspeaker was mounted in the door. (This noise was not seen in the harmonic analysis of the Boink test.) In comparison, Door 7 (Fig. 2) has much lower roughness values at all input voltages. A comparison of the two doors at the highest voltages illustrates this well (Fig. 3) and shows an increase in output from Door 7 of +5 dB over Door 2 for 20 – 160 Hz as well as the lower roughness values for Door 7. Figure 4 shows a similar comparison for mid level voltages. There is less of a difference in output levels at these voltages, but there is still more roughness for Door 2 (with levels around 2 aspers) compared to Door 7 (with levels mostly below 0.5 aspers).

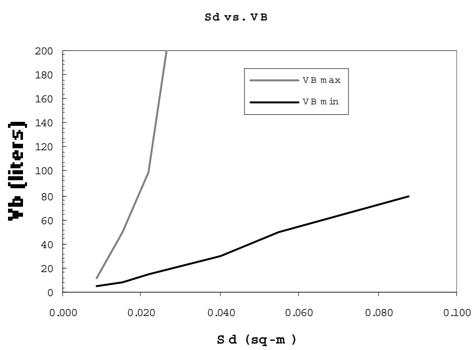
For the 0.610 m mic. distance data, both the loudspeaker and the trim radiation are sources in the roughness data. This is illustrated for Door 2 (Fig. 5), where additional roughness peaks are present due to the door trim, and it can be heard on the recordings. Again, Door 7 (Fig. 6) has much less roughness. Figure 6 is a zoom plot on the asper scale, and roughness peaks show up there at 55, 70, 100, and 200 Hz. These have roughness values, respectively, of 1.7, 1.5, 1.0, and 0.5 aspers. They are audible on the recording as door and trim buzzes and could be considered significantly distracting, but not nearly so much as Door 2 in comparison (Fig. 7 & 8). Also looking a Figure 8, there is still more output from Door 7 below 160 Hz, as was the case for the 25mm mic. distance. At intermediate voltage levels, there are more roughness peaks in Door 7 than before and they are attributed to the door & trim buzzes. Door 2 still has a higher density of roughness than Door 7. But for Door 7, it's interesting to note that the first peak is at 70Hz, with a value of approximately 1.5 aspers. We recall that this frequency of 70Hz corresponds closely with the second maxima in the impedance curve (67.8Hz), and that the roughness peak at 55 Hz with higher voltage corresponds to the first maxima in the impedance curve (55.1 Hz). We also recall that the system designer found the enclosure unusable below 60 Hz, and set the highpass filter in his equalization for that loudspeaker at 65 Hz.

6. Judgment Criteria

In general, we should design door enclosure systems with the available system components in mind. That is to say, if a highly compliant loudspeaker, with a large volume displacement, and high power handling capability is available, we could specify a closed-box seal on a door, and radiation free trim. If the volume was sufficiently large and the system amplification likewise, then that could work. And if the volume was not sufficiently large, the electronic processing to control the non-linearities of undersized enclosures could be used. If we are of more modest means and possess less than ideal door enclosures, then we must look for controlled mass loading improvements.

What kind of criteria does that leave us for judging the quality of a door enclosure?

1) The volume of the door should be sufficient for the chosen loudspeaker and amplification, using classical box theory. (Below.)



2) There should be sufficient baffling and sealing from leakage to provide the woofer with an improvement over free air performance, providing at least a 2nd Order low frequency turn on response
3) There should be controlled losses (apparent mass changes of 25% can be expected) and controlled trim radiation for enhanced low frequency output without added extraneous noise (roughness values less than 1 asper)
4) Any increase in apparent mass change should be investigated to ensure that there is neither no added stress applied to the woofer beyond its ability to sustain it nor any significant reduction in the woofer's transient behavior.

7. Conclusions

There are obvious limits to our understanding of the above criteria. The tools used in this study are effective for identifying some existing problems in a door design and improving it for that particular application, but limited in giving a general set of design parameters for door design. For instance, there is no clear understanding of the benefit or harm of the Type III reduced resonance type of door enclosure. As system designers we are aware of the phenomenon and take advantage of it, but it is also a large source of uncontrolled variability in the design, and potentially a reduction in transient behavior. There is a need for further investigation into the source of the different non-linear behaviors, which would provide a better model for design and quality assessment. This would include a more detailed assessment of the transient behavior of the different enclosure system. It would include mechanical dynamic behavior data in the form of displacement and acceleration measurements of the doors and trim and source identification through intensity measurements. And it would include the creation of the model. For now we have the stated criteria as general guidelines for volume size vs. loudspeaker size, sufficient baffling for at least a 2nd order low frequency response, controlled losses with apparent mass shifts, roughness targets of less than 1 aspers, and the precaution for protecting woofer's behavior in less than ideal enclosures.

8. Acknowledgements

We'd like to thank Dustin Vandeventer for his help in collecting data, John Stewart for his shared data, and Phil May for his help in collecting and analyzing the roughness data.

9. References

[1] R.H.Small "Closed-Box Loudspeaker Systems Part 1: Analysis" (JAES, Volume 20 Number 10 pp. 798·808; December 1972)

[2] R.H.Small "Closed-Box Loudspeaker Systems Part 2: Synthesis" (JAES, Volume 21 Number 7 pp. 549·554; September 1973)

[3] R.H. Small "Vented-Box Loudspeaker Systems Part 1: Small-Signal Analysis" (JAES, Volume 21 Number 5 pp. 363·372; June 1973)

[4] D. Keele "Development of Test Signals for the EIA-426-B Loudspeaker Power Rating Compact Disk", presented at the 111th Convention of the Audio Eng. Soc., New York (2001 September), Preprint 5451.

[5] R.H. Small "Vented-Box Loudspeaker Systems Part 1: Large-Signal Analysis

[6] W. Klippel "Fast and Accurate Measurement of Linear Transducer Parameters," presented at the 110th Convention of the Audio Eng. Soc., Amsterdam (May 2001)

[7] W. Aures, "Ein Berechnungsverfahren der Rauhigkeit," ("A Procedure for Calculating Auditory Roughness"), *Acustica*, vol. 58, pp. 268-281 (1985).

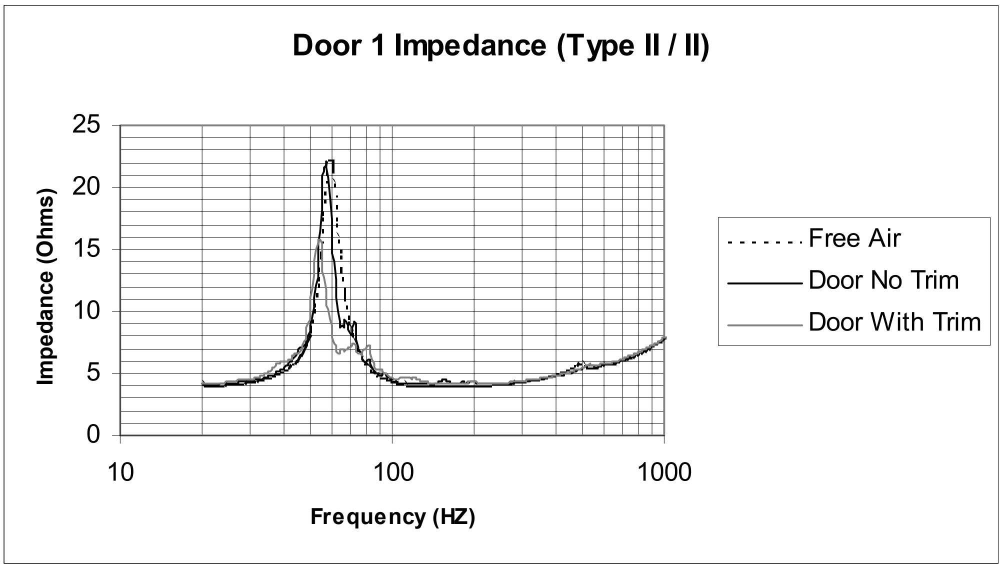
[8] E. Terhardt, “On the Perception of Periodic Sound fluctuations (Roughness),” *Acustica*, vol. 30, pp. 201-213 (1974).
[9] P. Daniel and R. Weber, “Psychoacoustical Roughness: Implementation of an Optimized Model,” Acustica-Acta Acustica, vol. 83, pp. 113-123 (1997).

10. Appendix 1

DOOR 1

Door Type: Large Sedan

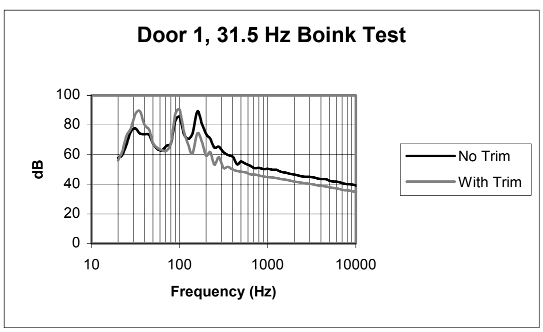
Door 1	Free Air	Door	With Trim
F	59.03	57.68	53.83
Q_m	7.56	6.18	8.50
Q_e	1.63	1.39	2.98
Q_t	1.34	1.13	2.21
V_D (liter)	0.07		
α		-0.17	0.67

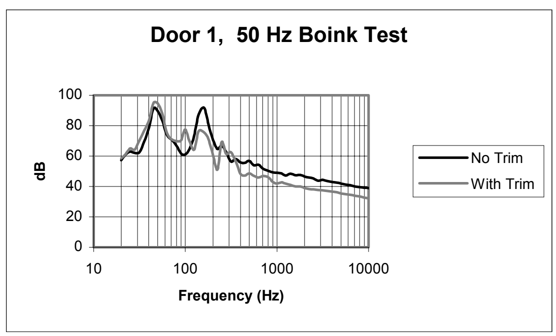


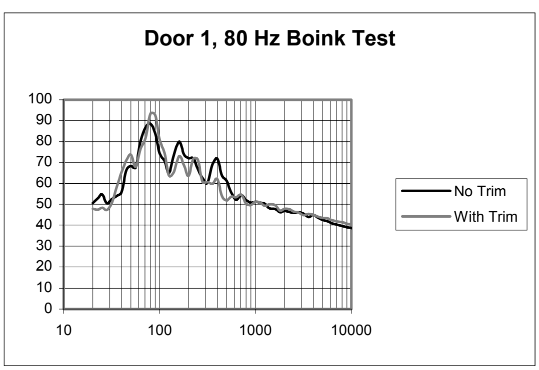
Type II Door Impedance: Skewing of the curve becoming asymptotic to the free air curves below resonance.

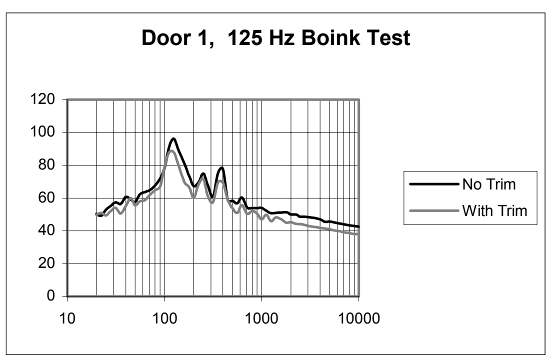
Appendix 1

DOOR 1





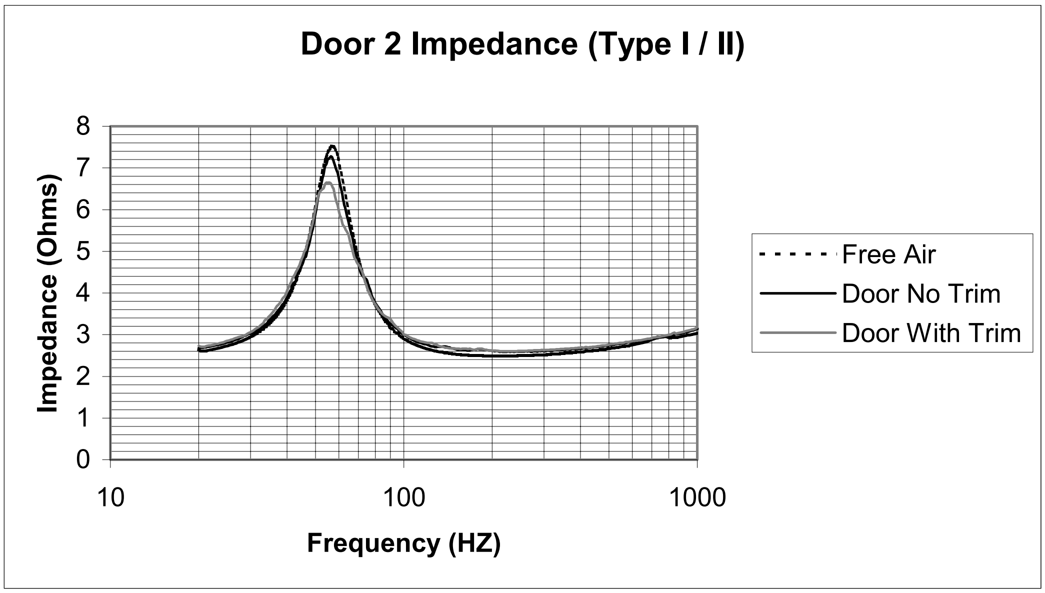




Appendix 1
DOOR 2

Door Type: Sports Coupe

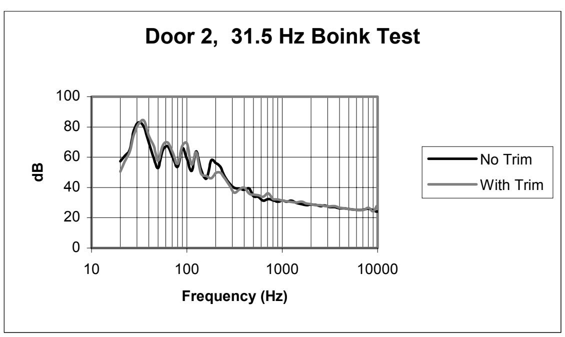
Door 2	**Free Air**	**Door**	**With Trim**
F	57.03	56.38	55.73
Q_m	3.28	3.04	2.56
Q_e	1.62	1.68	1.65
Q_t	1.09	1.08	1.00
V_D (liter)	0.05		
α		0.02	-0.01

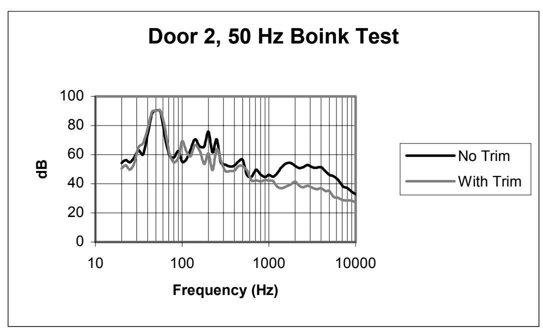


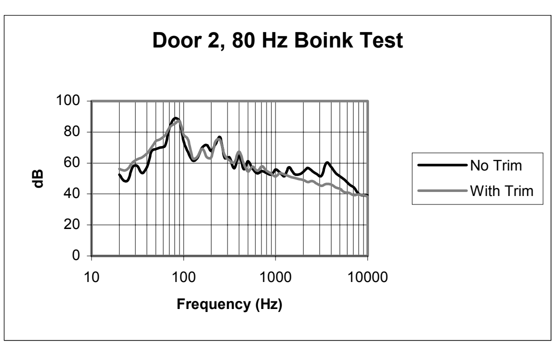
Type I Door Impedance: Minimal change from free air

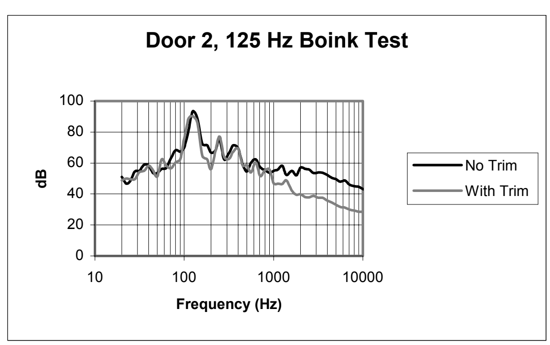
Appendix 1

DOOR 2





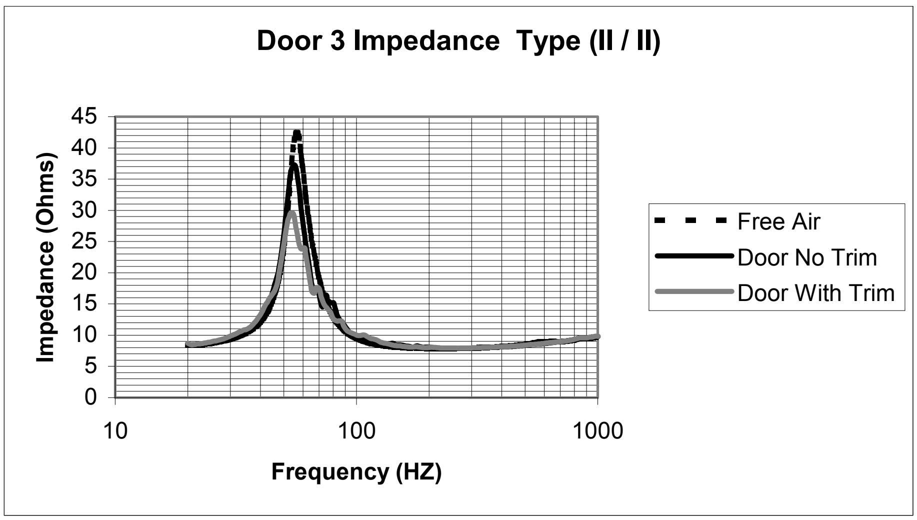




Appendix 1
DOOR 3

Door Type: Large Sedan

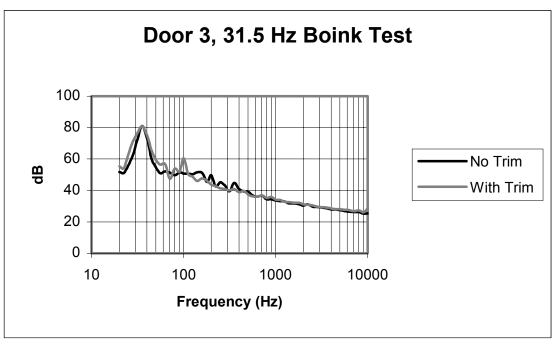
Door 3	Free Air	Door	With Trim
F	57.03	56.38	55.73
Q_m	3.28	3.04	2.56
Q_e	1.62	1.68	1.65
Q_t	1.09	1.08	1.00
V_D (liter)	0.08		
M_{ms}	15.03	19.00	
α		0.04	-0.04

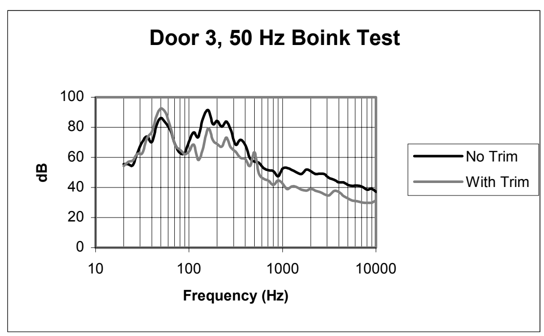


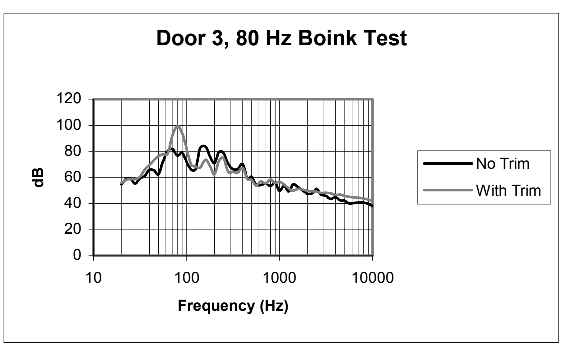
Type II Door Impedance: Skewing of the curve becoming asymptotic to the free air curves below resonance.

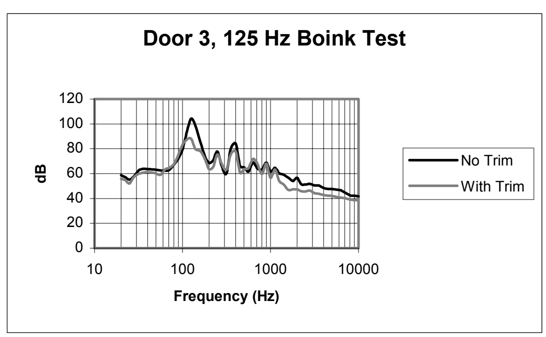
Appendix 1

DOOR 3





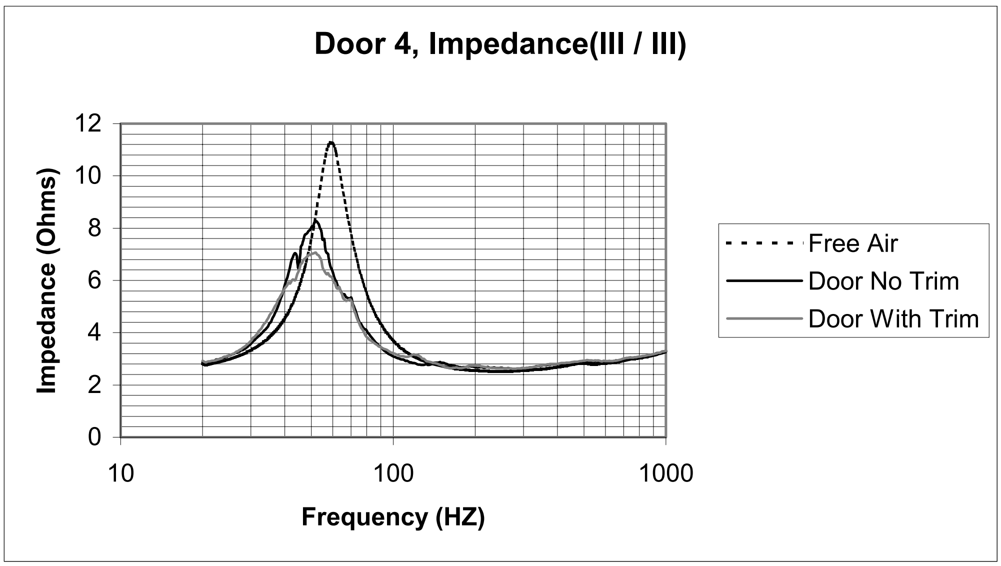




Appendix 1
DOOR 4

Door Type: Medium-Sized SUV

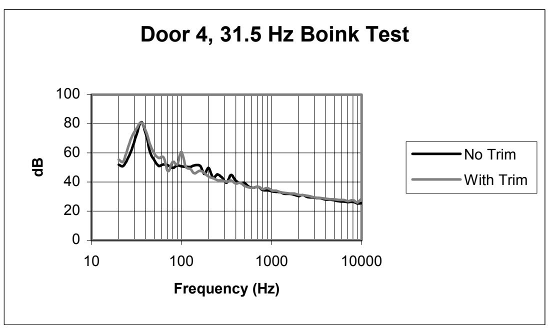
Door 4	Free Air	Door	With Trim
F	59.03	52.00	52.00
Q_m	3.31	2.49	2.03
Q_e	0.95	1.16	1.20
Q_t	0.74	0.79	0.75
V_D (liter)	0.11		
M_{ms}	12.00	12.43	
α		0.07	0.11

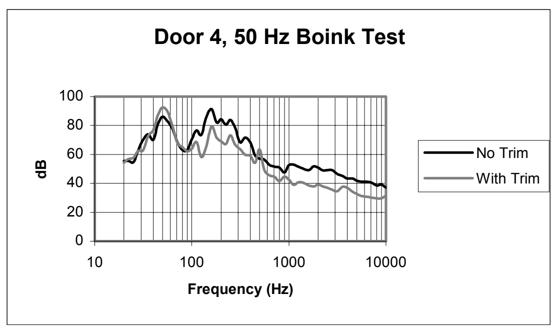


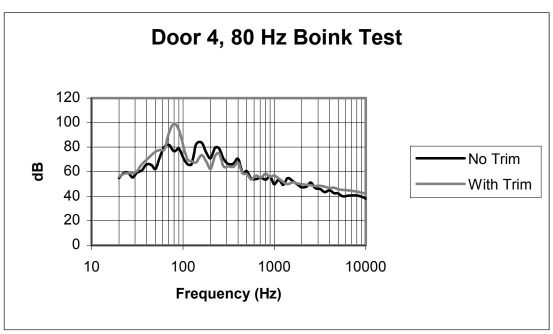
Type III Door Impedance: Complete resonance shift down in frequency.

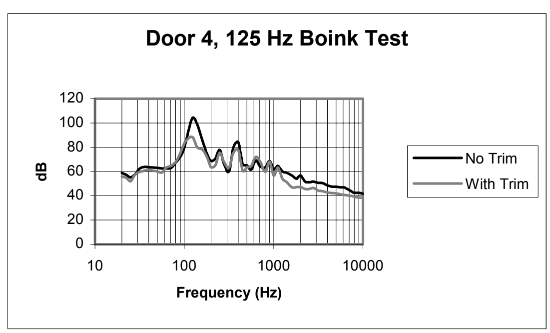
Appendix 1

DOOR 4





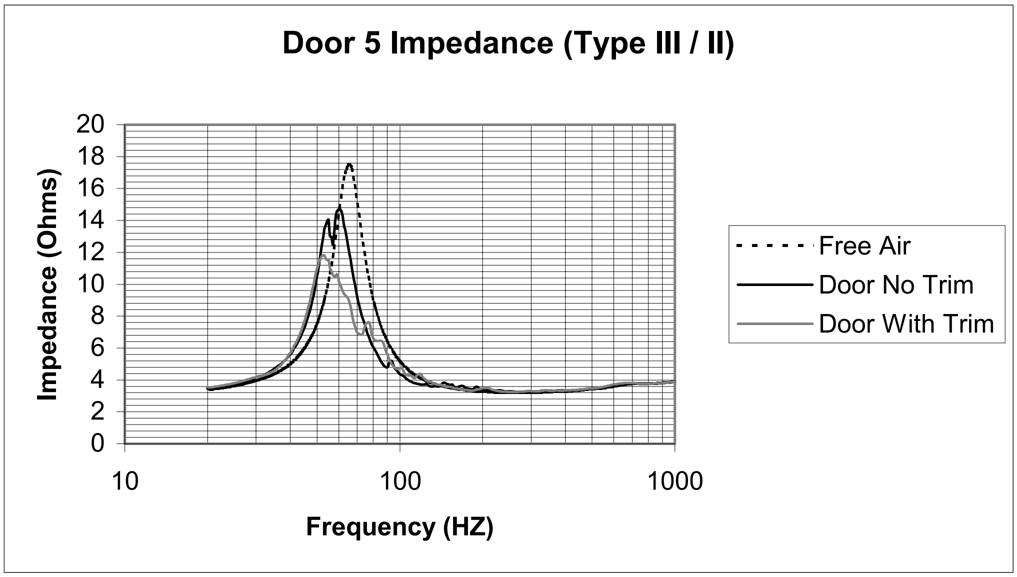




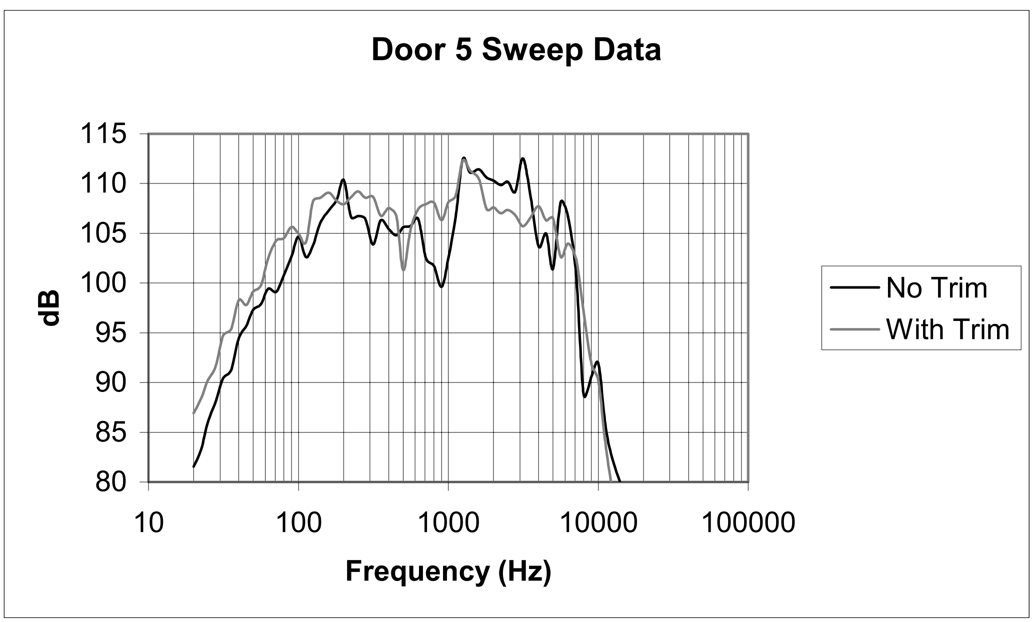
Appendix 1
DOOR 5

Door Type: Medium-Sized SUV

Door 5	Free Air	Door	With Trim
F	65.48	60.40	52.60
Q_m	4.41	3.98	2.18
Q_e	0.99	1.13	0.83
Q_t	0.81	0.88	0.60
V_D (liter)	0.04		
M_{ms}	10.08	12.56	
α		0.05	-0.33

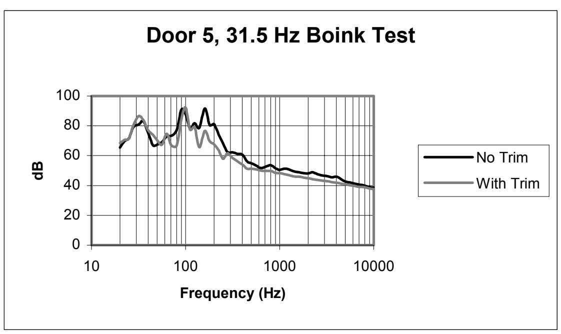


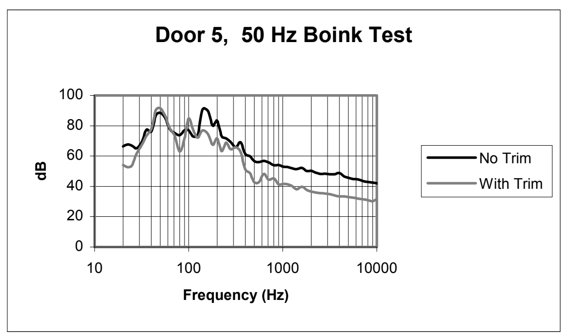
Type II Door Impedance: Skewing of the curve becoming asymptotic to the free air curves below resonance.

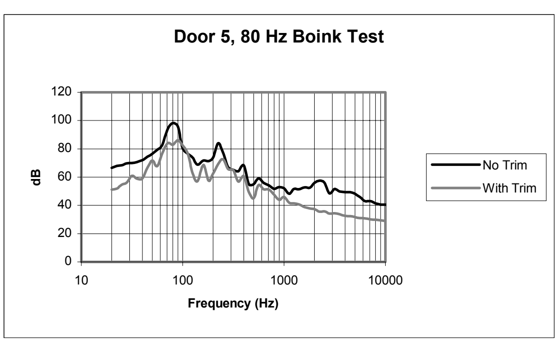


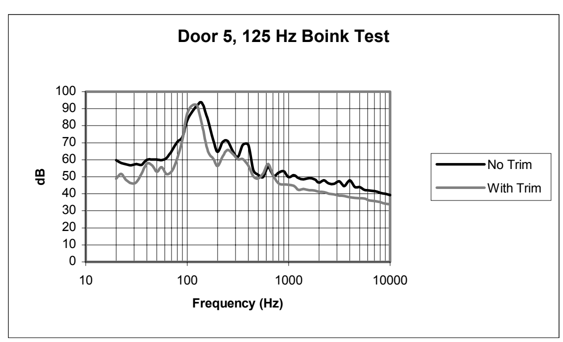
Appendix 1

DOOR 5





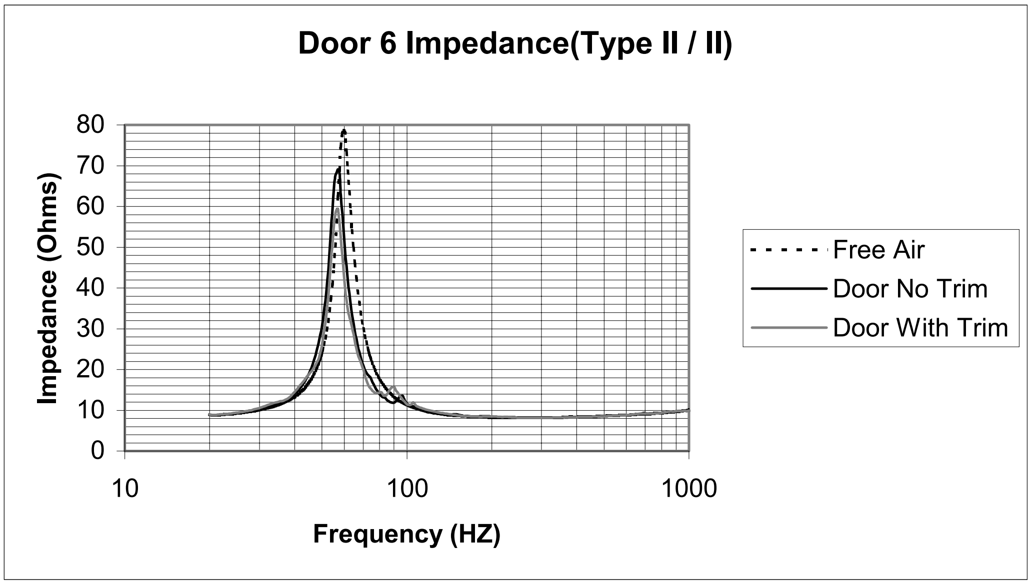




Appendix 1
DOOR 6

Door Type: Coupe

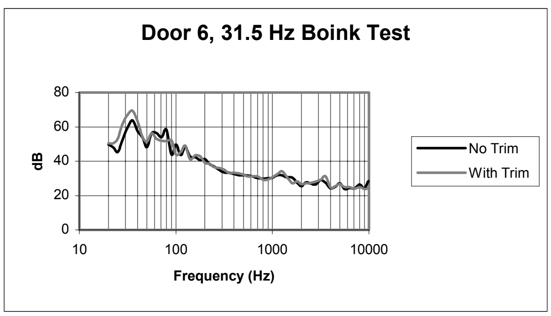
Door 6	Free Air	Door	With Trim
F	59.70	57.03	57.03
Q_m	8.29	7.85	7.99
Q_e	0.96	1.05	1.27
Q_t	0.86	0.93	1.10
V_D (liter)	0.07		
α		0.05	0.27

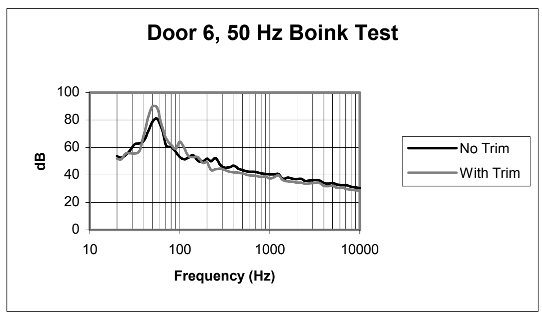


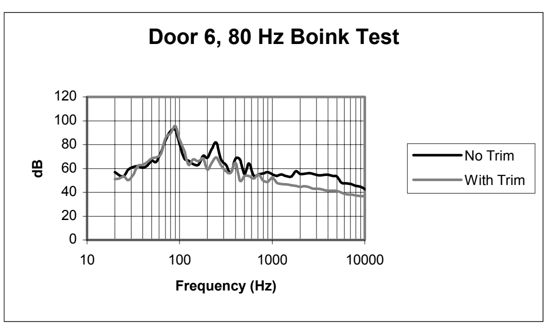
Type III Door Impedance: A complete resonance shift down in frequency.

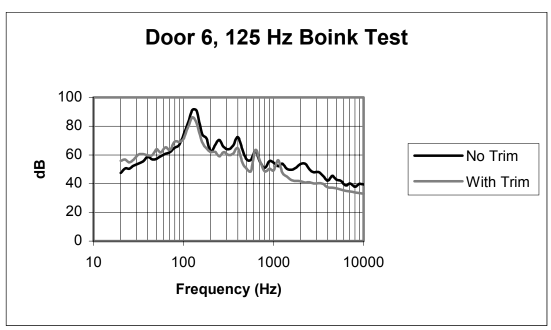
Appendix 1

DOOR 6





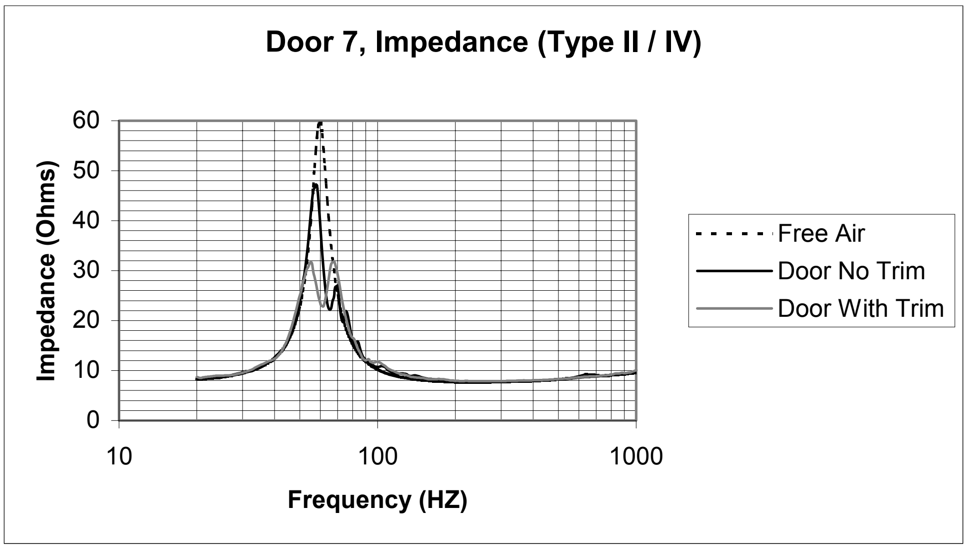




Appendix 1
DOOR 7

Door Type: Large Sedan

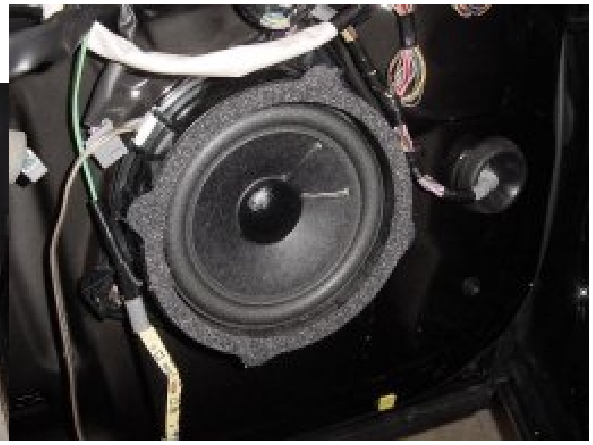
Door 7	Free Air	Door	With Trim
F	60.40	57.68	67.78
Q_m	7.52	6.72	7.43
Q_e	1.11	1.33	1.10
Q_t	0.97	1.11	0.96
V_D (liter)	0.07		
α		0.14	0.04
Q_L			7.80

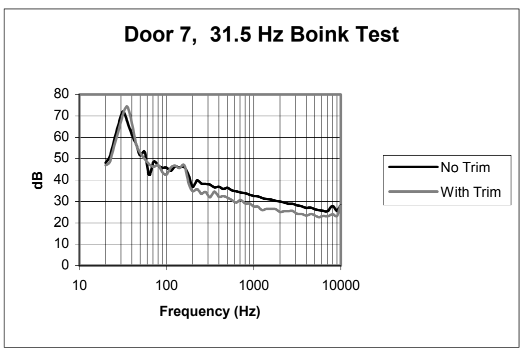


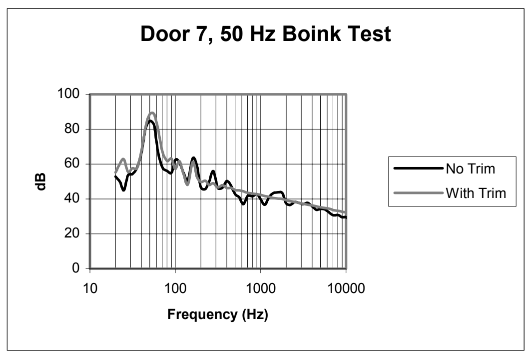
Type II Door Impedance: Skewing of the curve becoming asymptotic to the free air curves below resonance.

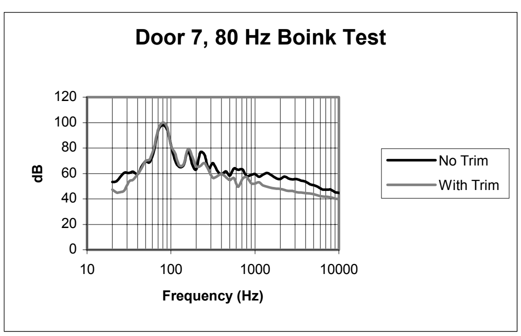
Appendix 1

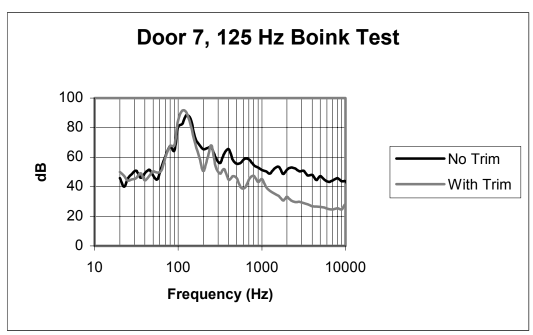
DOOR 7







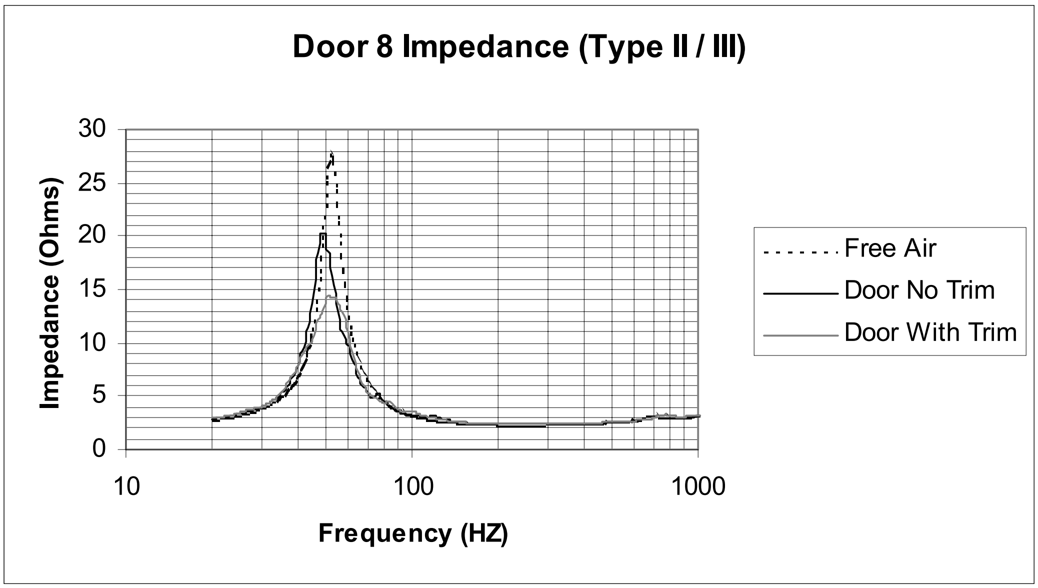




Appendix 1
DOOR 8

Door Type: Medium-Sized SUV

Door 8	Free Air	Door	With Trim
F	52.00	49.10	51.40
Q_m	7.43	5.50	3.89
Q_e	0.68	0.72	0.77
Q_t	0.62	0.64	0.64
V_D (liter)	0.09		
α		0.01	0.12

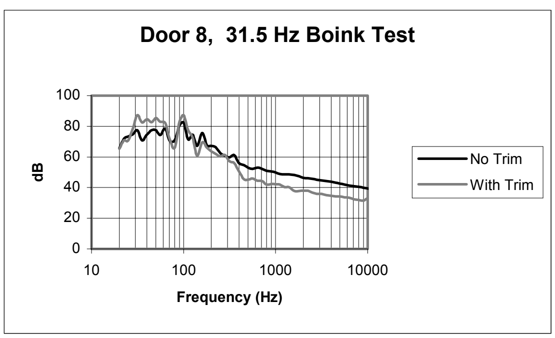


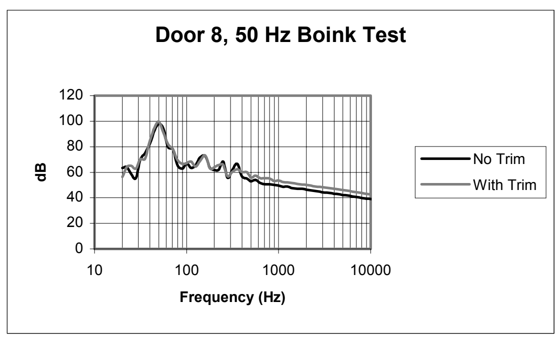
Type II Door Impedance: Skewing of the curve becoming asymptotic to the free air curves below resonance.

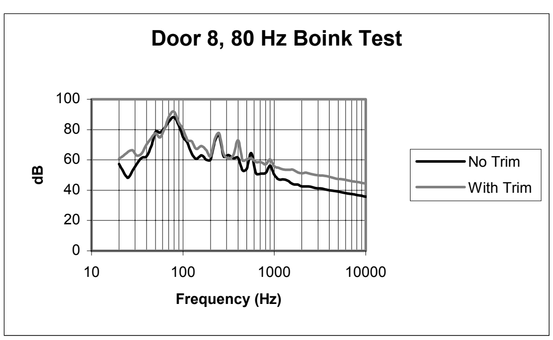
Appendix 1

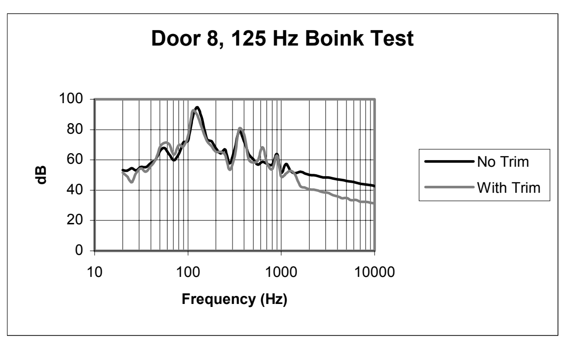
DOOR 8



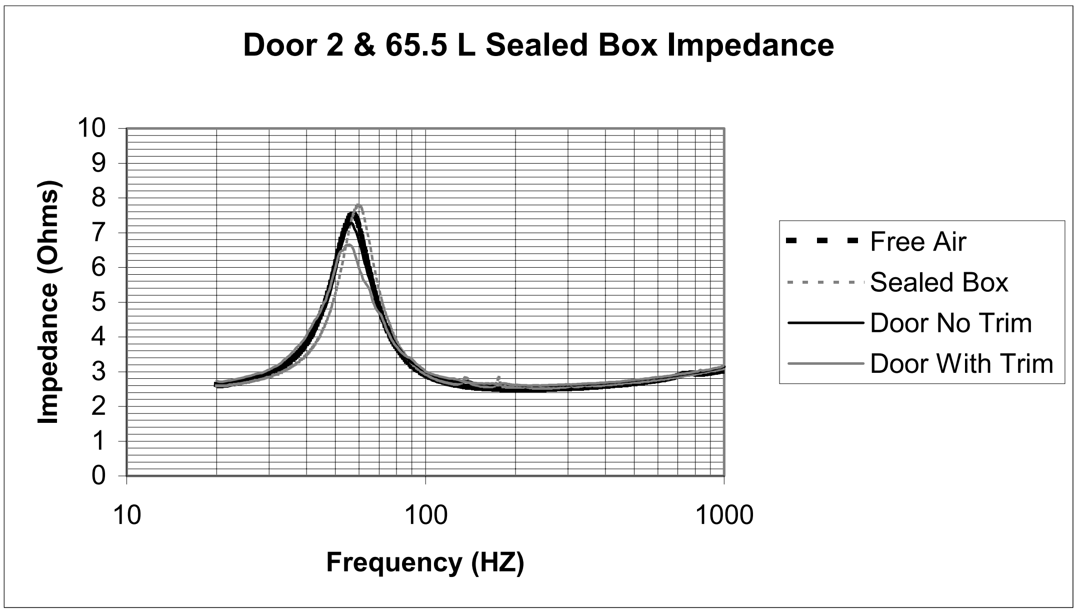


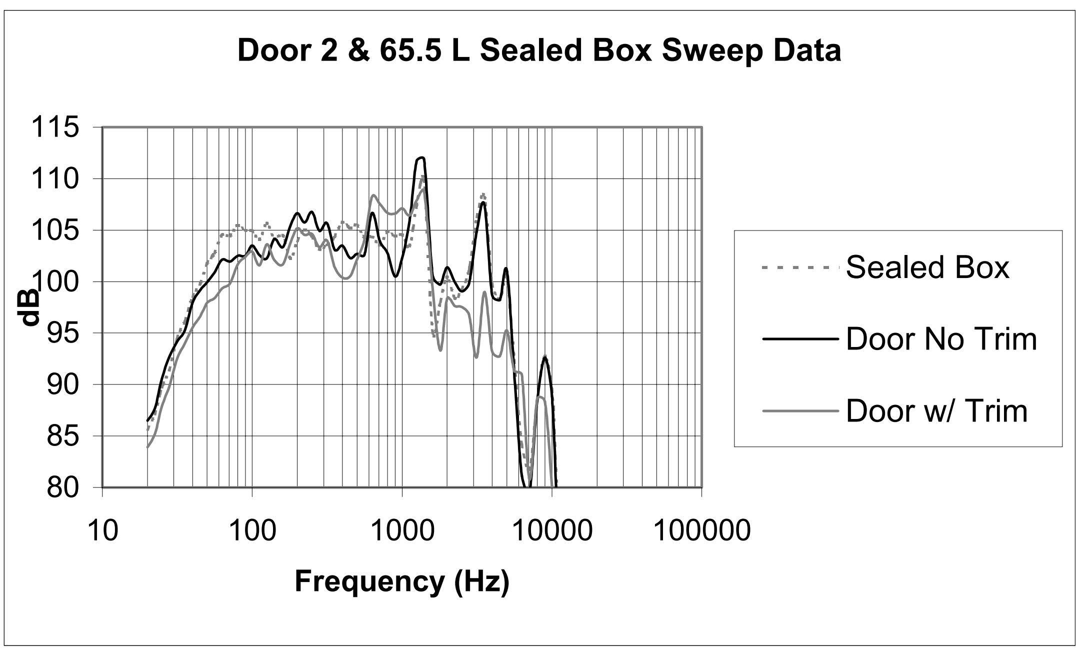




Appendix 1
DOOR 2 & Sealed Box

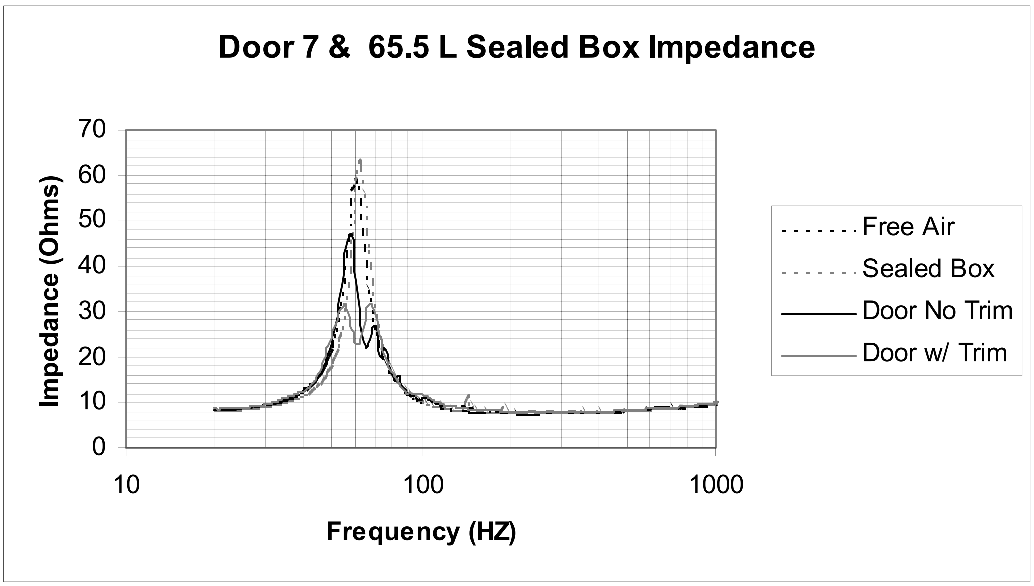
Door 2 & Sealed Box		Free Air	Sealed Box	Door	With Trim
	F	57.03	59.70	56.38	55.73
	Q_m	3.28	3.64	3.00	2.56
	Q_e	1.62	1.74	1.65	1.65
	Q_t	1.09	1.18	1.07	1.00
	V_D (liter)	0.05			
	α		0.12	0.01	-0.12

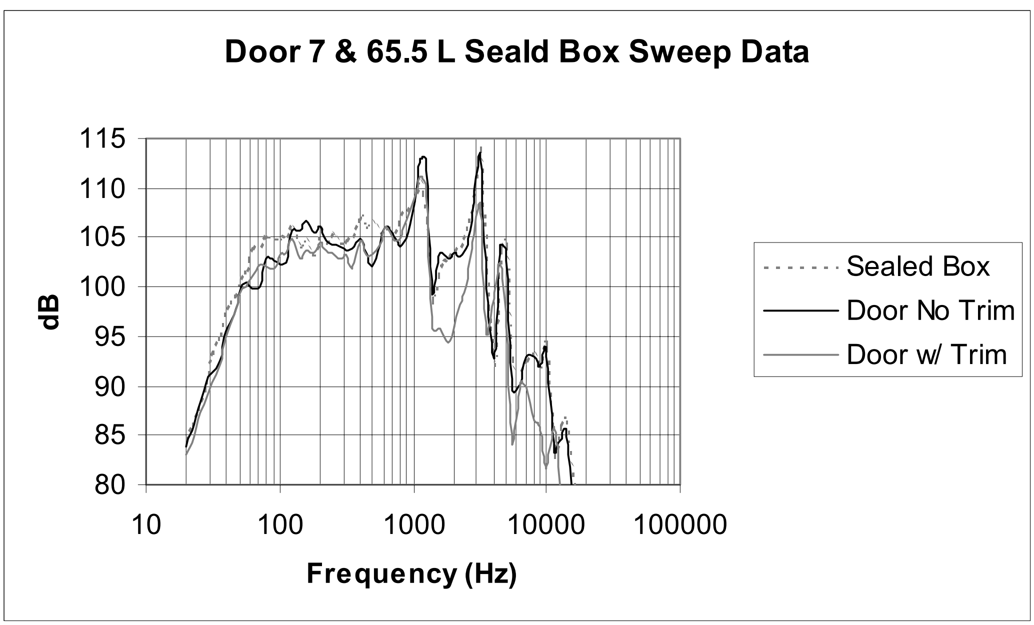




Appendix 1
DOOR 7 & Sealed Box

Door 7 & Sealed Box		Free Air	Sealed Box	Door	With Trim
	F	60.40	61.80	57.68	67.78
	Q_m	7.52	7.88	6.72	7.43
	Q_e	1.11	1.11	1.33	1.10
	Q_t	0.97	0.98	1.11	0.96
	V_D (liter)	0.07			
	α		0.02	0.14	0.04
	Q_L				7.80





11. Appendix 2

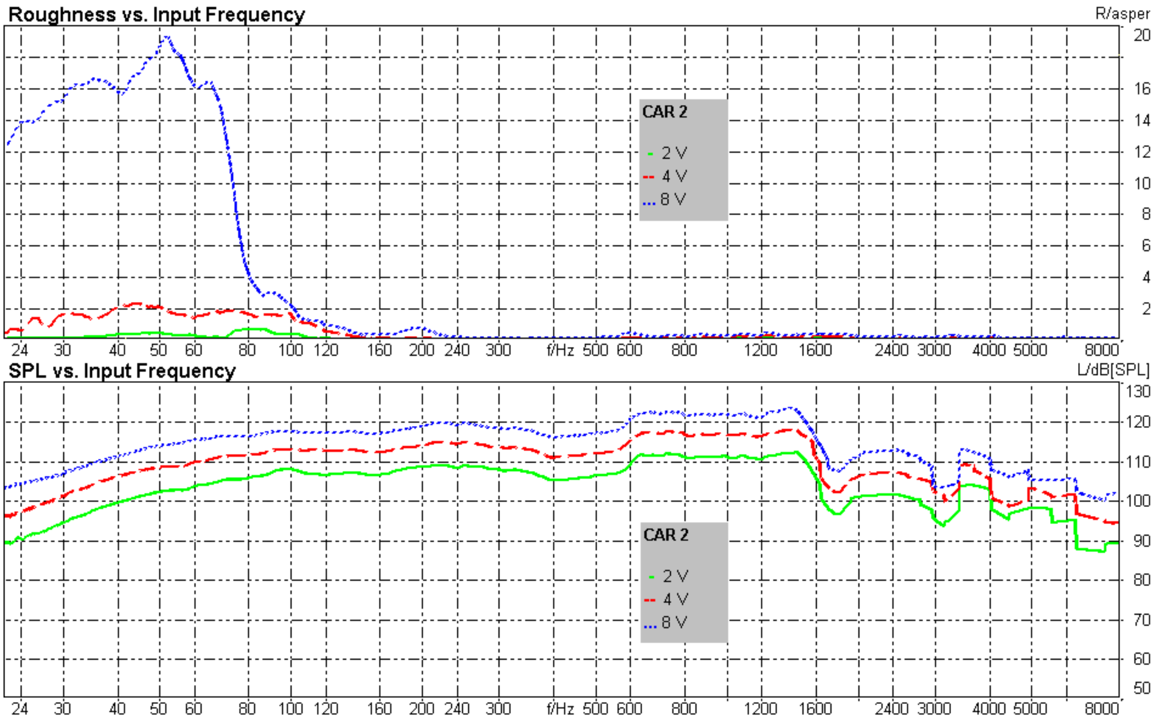


Figure 1: (25mm mic distance) Roughness and SPL vs. input frequency for Door 2 using 2, 4, and 8 V swept sine inputs

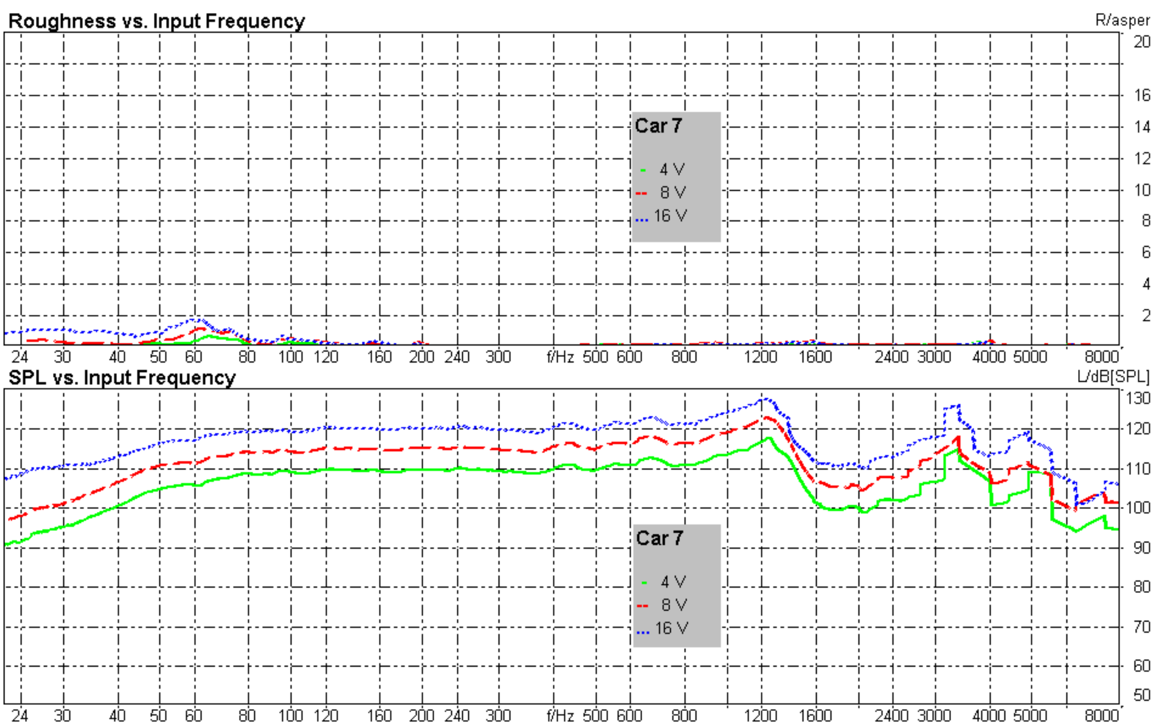


Figure 2: (25 mm mic distance) Roughness and SPL vs. input frequency for Door 7 using 4, 8, and 16 V swept sine inputs

Appendix 2

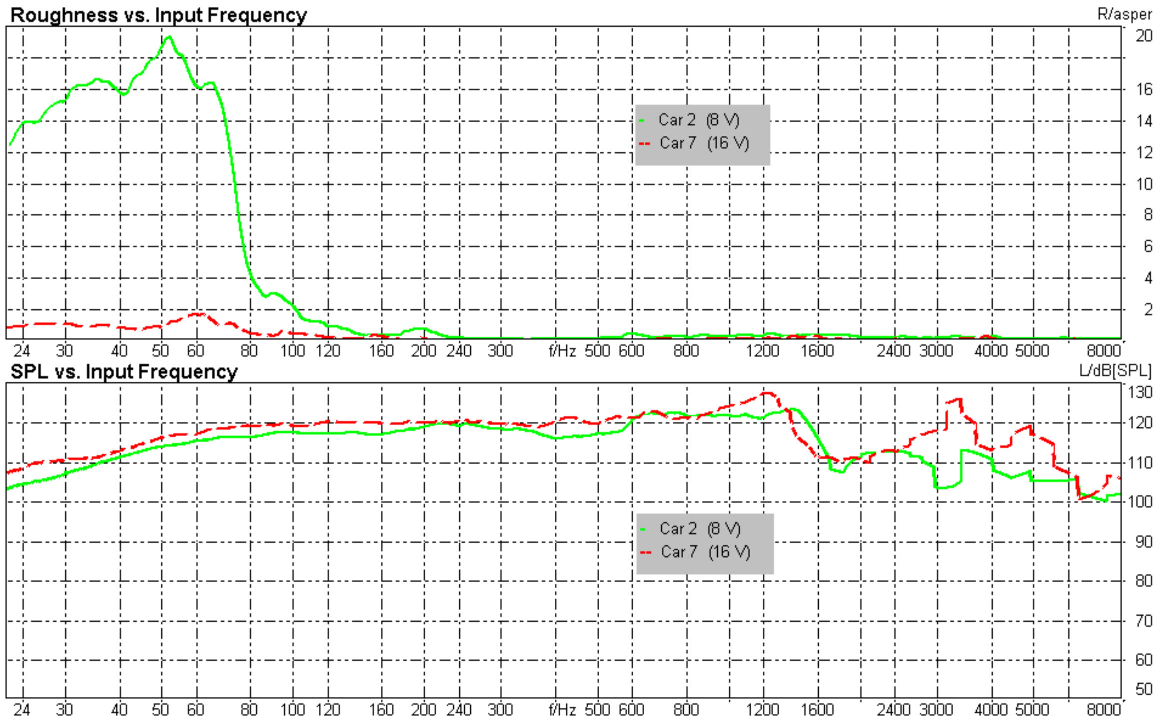


Figure 3: (25 mm mic distance) Door 2 and Door 7 recordings made with equal input power to the loudspeakers (2 and 8-ohms, 8V and 16V respectively)

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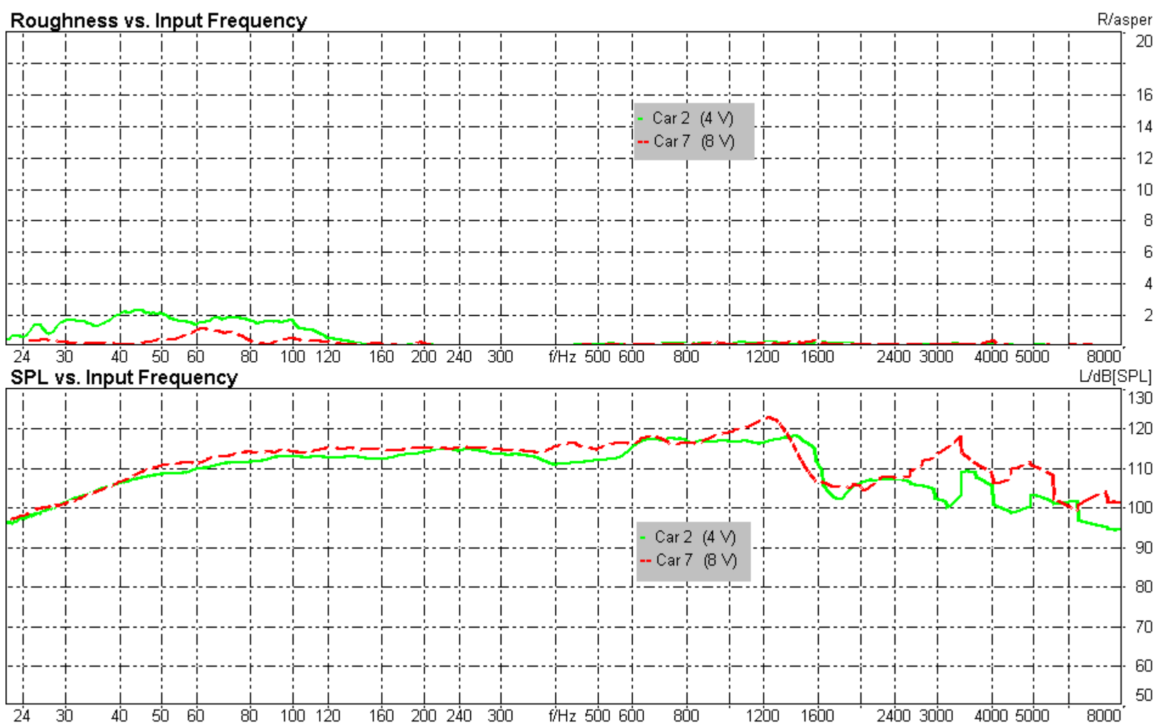

Figure 4: (25 mm mic distance) Door 2 and Door 7 recordings made with equal input power to the loudspeakers (2 and 8-ohms, 4V and 8V respectively).

Appendix 2

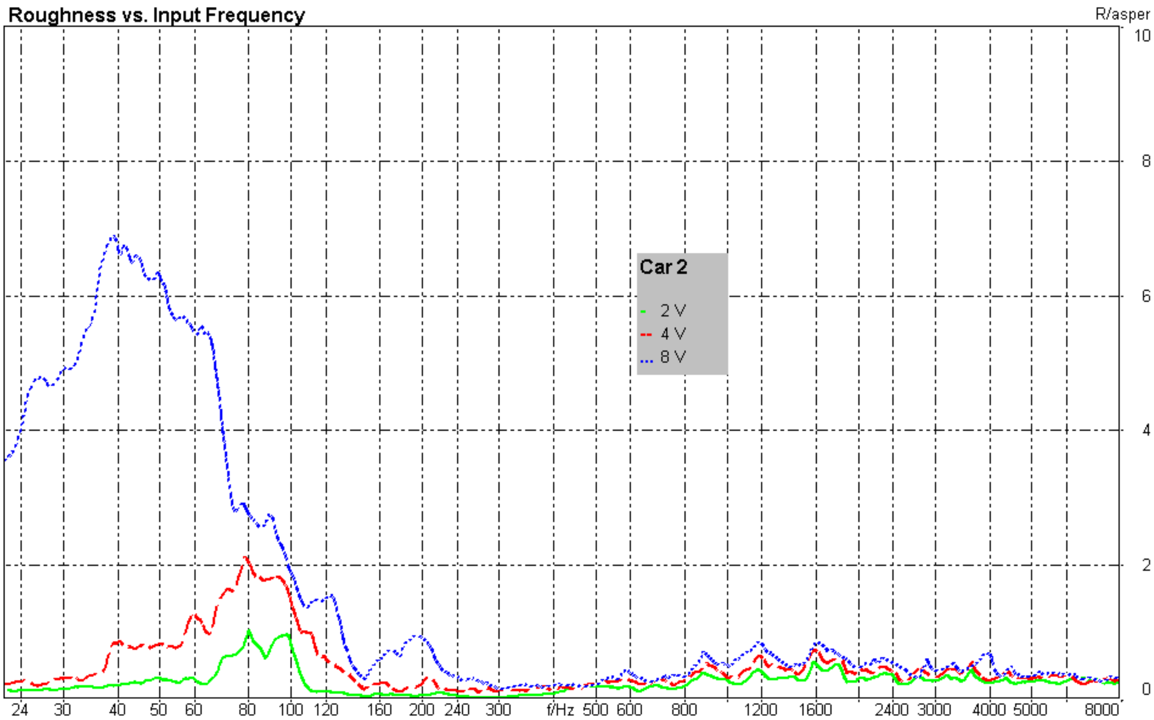

Figure 5: (0.610 m mic distance) Roughness and SPL vs. input frequency for Door 7 using 4, 8, and 16 V swept sine inputs

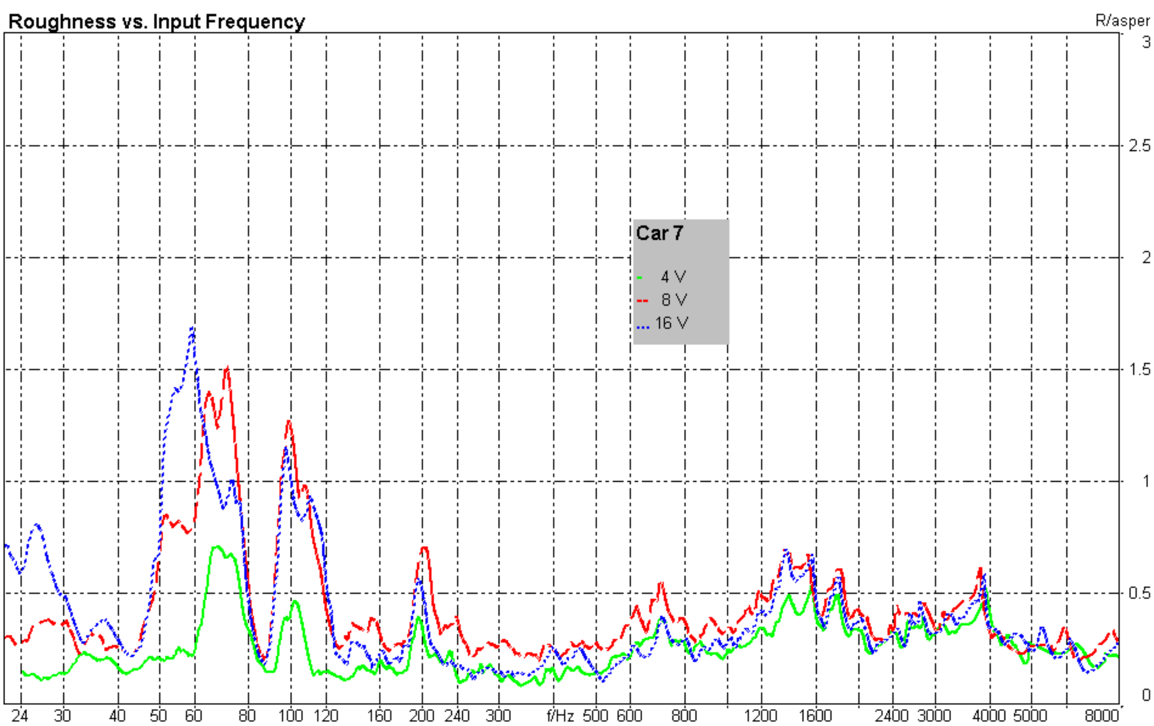

Figure 6: (0.610 m mic distance) Roughness and SPL vs. input frequency for Door 7 using 4, 8, and 16 V swept sine inputs. (asper scale Zoom In)

Appendix 2

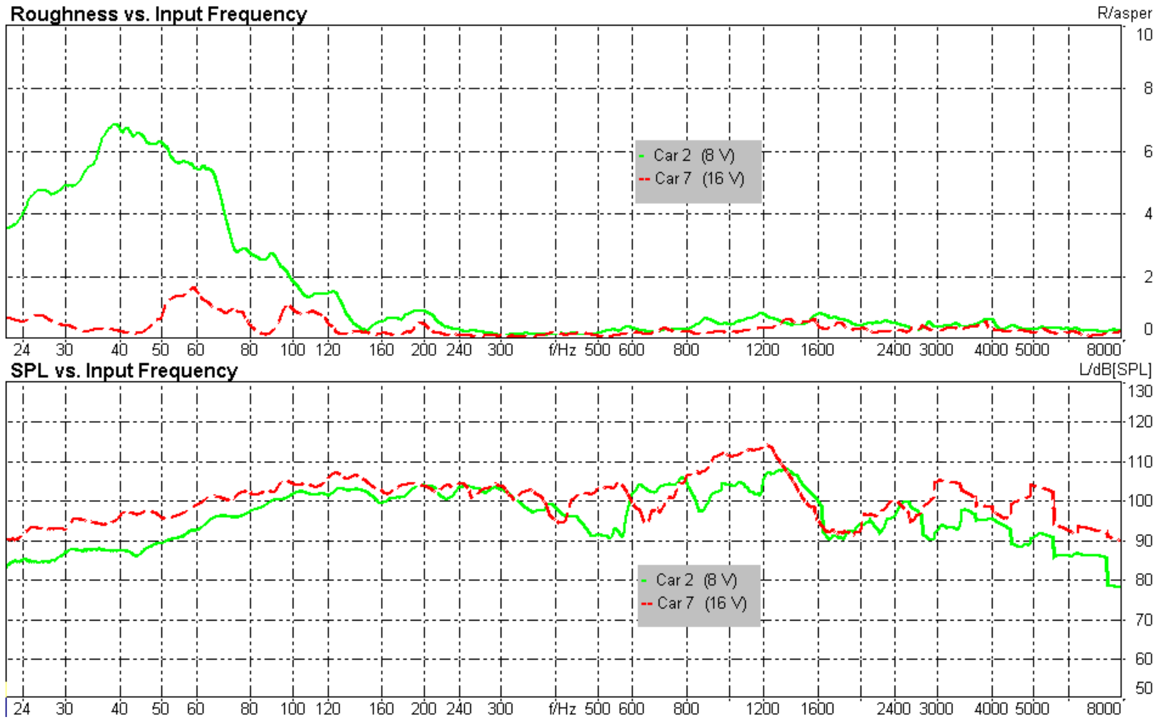

Figure 7: (0.610 m mic distance)) Door 2 and Door 7 recordings made with equal input power to the loudspeakers (2 and 8-ohms, 8V and 16V respectively)

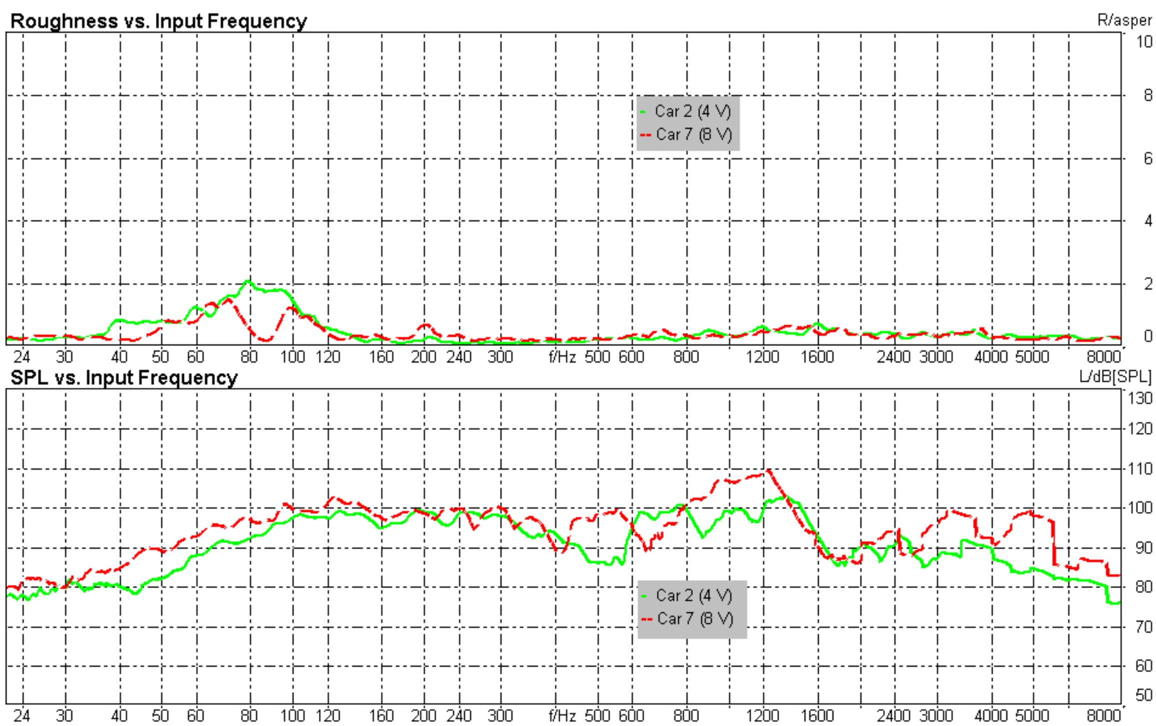

Figure 8: (0.610 m mic distance)) Door 2 and Door 7 recordings made with equal input power to the loudspeakers (2 and 8-ohms, 4V and 8V respectively)