The Car Audio System Nobody Would Build part 2

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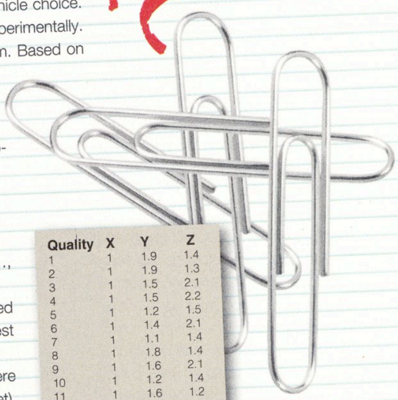
In the first part of this series, I discussed why I chose a Dodge (Mercedes-built) Sprinter 3500 SHC cargo van as the platform for a competition vehicle. This part delves deeper into the reasoning for this unorthodox vehicle choice. I'll determine the Sprinter's interior dimensions, and resulting resonance modes, both theoretically and experimentally. In addition, I'll experimentally determine the room gain, or "transfer function" across the frequency spectrum. Based on the experimental data, appropriate damping and barrier materials will be selected and installed.



Calculating Resonance Modes

Last time, I discussed the importance of favorable room dimensional ratios to evenly distribute room resonances. Axial resonance modes of a room may be calculated using the equation[1]:

$$f_m = \frac{mv_s}{2d}$$

Where f_m is the frequency of resonance mode m, m is the integer value of the resonance mode (1, 2, 3, …, m), v_s is the speed of sound in air, and d is the distance between the walls of interest.

In order to optimally distribute axial resonance modes in a room, extensive research has been conducted to determine the best dimensional ratios of a room. Table 1 shows, in order of descending quality, the best dimensional room ratios determined by M. M. Louden.[2]

The principle dimensions in meters and feet for the length, width, and height of the Sprinter interior were estimated from a CAD drawing to be 5.388m (17.68 feet), 1.684m (5.525 feet), and 1.855m (6.086 feet), respectively. The following room dimensional ratios were determined:

Height/width = 1.855/1.684 = 1.102

Length/width = 5.388/1.684 = 3.200

It should be noted that multiples of any dimension are also equally valuable. For instance, any value in the Y or Z columns could be doubled without detriment. From Table 1, it can be seen that the dimensional room ratios of the Sprinter rank 19th among the best dimensional room ratios, where the width corresponds to 1.0, the height corresponds to 1.1, and the length corresponds to 1.6, because the length at 3.2 is an exact multiple of 1.6. (See Table 1)

Quality	X	Y	Z
1	1	1.9	1.4
2	1	1.9	1.3
3	1	1.5	2.1
4	1	1.5	2.2
5	1	1.2	1.5
6	1	1.4	2.1
7	1	1.1	1.4
8	1	1.8	1.4
9	1	1.6	2.1
10	1	1.2	1.4
11	1	1.6	1.2
12	1	1.6	2.3
13	1	1.6	2.2
14	1	1.8	1.3
15	1	1.1	1.5
16	1	1.6	2.4
17	1	1.6	1.3
18	1	1.9	1.5
19	1	1.1	1.6
20	1	1.3	1.7

Table 1. Favorable dimensional room ratios.

Given the speed of sound in air to be 344.42m/s (1,130ft/s), the axial resonance modes were calculated according to Equation 1. Table 2 shows the first 26 axial resonance modes for the length, width, and height. Figure 1 graphically represents the distribution of resonance modes. Although the distribution of resonance modes is reasonably uniform, both Table 2 and Figure 1 show three individual modes L_3 (96Hz), W_1 (102Hz), and H_1 (93Hz) that are grouped more closely to one another than the rest of the modes. Continuing higher in frequency, two more modes, L_6 (192Hz) and H2 (186Hz), are grouped more closely to one another as well. It would be reasonable to expect the van's frequency response to be altered by the presence of these more closely spaced modes and the lower fundamental modes at 32 and 64Hz. Although there are two coincident modes at 511Hz (L16 and W5), a seemingly undesirable situation, it's generally accepted by acousticians that modes above 300Hz are of little or no concern.[3] The relevance of these theoretical predictions to actual measurements will be discussed later in this article.

Based on the interior dimensions of the Sprinter van, the internal volume was determined to be 16.83m^3 (594.4ft^3), very close to my initial goal of about 600ft^3, favorable for achieving appropriate reverberation times. (See Table 2 and Figure1)

Mode	Length	Width	Height
1	32	102	93
2	64	205	186
3	96	307	279
4	128	409	371
5	160	511	464
6	192	614	557
7	224	716	650
8	256	818	743
9	288	920	836
10	320	1023	928
11	352	1125	1021
12	384	1227	1114
13	416	1329	1207
14	447	1432	1300
15	479	1534	1393
16	511	1636	1485
17	543	1738	1578
18	575	1841	1671
19	607	1943	1764
20	639	2045	1857
21	671	2148	1950
22	703	2250	2042
23	735	2352	2135
24	767	2454	2228
25	799	2557	2321
26	831	2659	2414

Table 2. Axial resonance modes.

In Part 1, the impact of room volume on room gain was discussed. Given the internal volume of 594.4 ft^3, the room gain was likely to be between 5 and 20dB at 20Hz. Not only was the low frequency boost of interest, but also the vehicle's room gain, or "transfer function," across the entire frequency spectrum. Determination of the transfer function would provide design input parameters for the calculation of amplifier power requirements, the optimization of loudspeaker enclosure parameters, and the selection of damping and barrier materials.

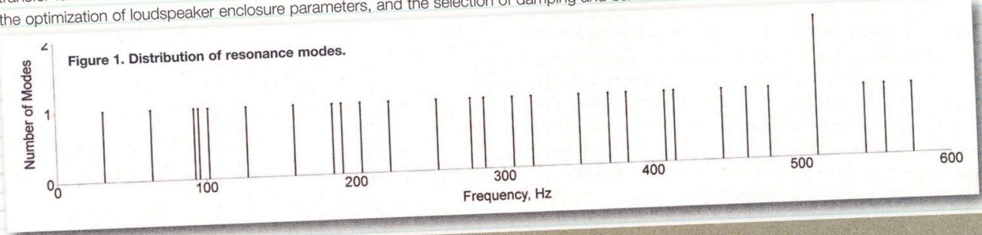


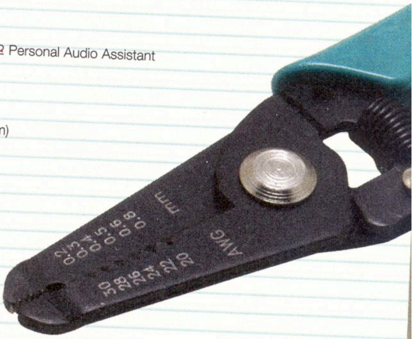
Figure 1. Distribution of resonance modes.

Transfer Function

I determined the transfer function of the Sprinter van by first measuring the response of a high-fidelity fullrange loudspeaker in a free-field, then measuring the response of the same loudspeaker placed inside the Sprinter. The difference between the loudspeaker response in a free-field and in the enclosed environment (closed-field) constitutes the vehicle's transfer function. It's important to note that the free-field frequency response of a loudspeaker is difficult to determine accurately, even under ideal laboratory conditions.[4,5] The equipment used and methods employed were readily available and practical but at best, an estimation.

The following equipment was used:

1. A 31-band real-time spectrum analyzer with a built-in omni-directional microphone, 0.5dB resolution, PAA2 Personal Audio Assistant ("PAA2"), Phonic Corporation of America
2. Laptop computer (Apple G4 17-inch, 1GHz CPU, 1GB RAM, System OS 10.3.7)
3. Spectrum analyzer computer interface software, Windows-based, Phonic Corporation of America
4. RS-232 interface cable for PAA2
5. Microsoft Office 2004 for the Mac (with Virtual PC 7.0.1 running Windows XP Professional operating system)
6. Music playback software Apple iTunes 4.7.1
7. USB-to-serial adapter Keyspan PN USA-19HS
8. Keyspan software driver for Macintosh OS 10.3.X
9. Digital Multimeter, Micronta model number 22-185A, Radio Shack
10. Audio amplifier, Adcom, model number GFA-545II
11. Audio loudspeaker, Vandersteen Audio, model number 2Ce
12. Audio preamplifier, Conrad-Johnson, model number PV10A
13. Audio interconnects, Kimber Kable, model PBJ, 1-meter pair, 2 pair required.
14. Mini audio microphone jack to RCA stereo adapter, Radio Shack
15. Loudspeaker cable, Kimber Kable, model 4TC, approximately 70ft (21m)
16. Audio software, "Pink Noise (20Hz to 20KHz) Right Channel Only," Autosound 2000, Test CD#102
17. Ladder
18. Measuring tape



In order to determine the free-field loudspeaker response, I set up the audio playback equipment in a garage according to each of the manufacturer's instructions. Since only one loudspeaker was used, only the right channel was configured for playback. According to Vandersteen's recommendations, I biwired the loudspeaker. The length of each speaker cable was about 35 feet (11m), which is a sufficient length to extend from the workbench, where the audio equipment was positioned, to the loudspeaker positioned in my driveway.


Figure 2. Audio Test Equipment.

The loudspeaker was oriented in such a way that the nearest object to the front or side was in excess of 100 feet. A small ladder was used to position and support the PAA2 so that the microphone was a meter (3.28 feet) in front of the loudspeaker and on axis with the tweeter. The PAA2 was programmed to record sound using A-weighting, the 30 to 90dB measurement range, and a 250 milliseconds response time. The digital multimeter was configured to measure the RMS voltage across the positive and negative amplifier speaker binding posts for the right channel. The "pink noise" audio track was played and the volume of the preamplifier was adjusted to achieve an RMS voltage of 2.83 volts across the speaker binding posts. The preamplifier volume setting remained unchanged for the remainder of the experiments. The "pink noise" audio track was played while three measurements were taken and stored to memory. The data stored in memory was imported into the PAA2's Windows-based software and saved as a comma-delimited text file. The comma-delimited text file was imported in Microsoft Excel 2004 for the Mac. The mean SPL was calculated for each of the 31 frequency bands.

To determine the closed-field frequency response, the same test-bench setup was used, but the loudspeaker was positioned inside the Sprinter. First, the closed-field response was determined in the cargo area. The loudspeaker was positioned about 5 feet (1.5m) behind the driver and passenger seats, facing in the forward direction (see Figure 3). All doors and windows were completely closed. A small ladder was used to position and support the PAA2 such that the microphone was one meter (3.28 feet) in front of the loudspeaker and on axis to the tweeter. Three measurements were taken using exactly the same technique as previously described.

Second, the closed-field frequency response was determined for the cockpit area at the driver's listening position. For this setup, the loudspeaker was repositioned as far forward as possible in the cargo area in an effort to excite the cockpit area (see Figure 3). The PAA2 was held by hand with the microphone facing forward in a position that approximated the location of a driver's head. Again, three measurements were taken using exactly the same technique as previously described. (See Figure 3)

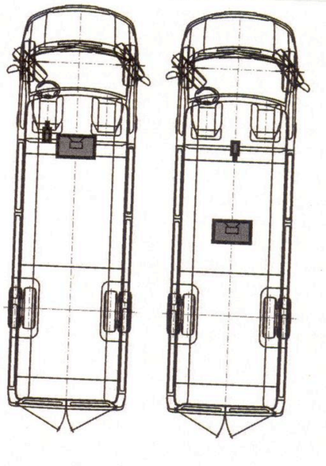
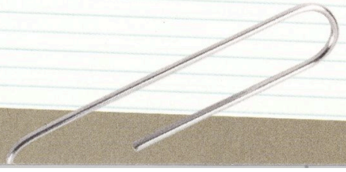


Figure 3. Setup used to determine vehicle transfer function. The upper and lower floor plans show the setups used to determine the cargo area and listening position closed-field frequency responses, respectively.



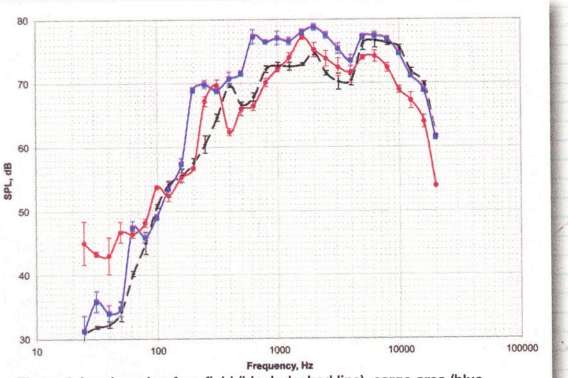


Figure 4. Loudspeaker free-field (black dashed line), cargo area (blue squares), and driver's listening position (red circles) A-weighted frequency response. Uncertainty bars represent the standard deviation of the three measurements.

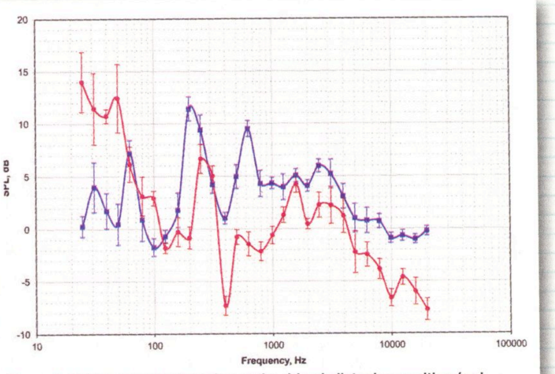


Figure 5. Vehicle transfer function at the driver's listening position (red circles) and in the cargo area (blue squares). Uncertainty bars were derived from standard uncertainty propagation techniques.

Figure 4 compares the reduced test data for the free-field and closed-field responses. To determine the vehicle's transfer function, the free-field response was subtracted from the closed-field responses and plotted. The uncertainty associated with each of the measurements was propagated according to standard practices.[6] Figure 5 shows the vehicle's transfer function at the driver's listening position and in the cargo area. There was substantial room gain at low frequencies at the driver's listening position, as much as 14dB at 25Hz. The room gain decreased as the frequency increased to about 110Hz, beyond which the room gain was negligible. Higher in the frequency spectrum, there was a peak at 250Hz of 7dB in magnitude followed by a dip at 400Hz of 7dB in magnitude. Another peak was evident at 1,600Hz of 4dB in magnitude. The higher treble frequencies (greater than 5KHz) were rolled off at the driver's seat; however, this was believed to be an artifact of the test setup, where the microphone was not only off-axis from the tweeter but also aimed toward the direction of sound propagation. Obviously, the microphone was measuring reflected, attenuated sound. Clearly, 14dB of room gain at the lowest frequencies will substantially reduce the amplifier power requirements and augment any low-frequency roll-off associated with the loudspeaker enclosures.

The cargo area transfer function, shown in Figure 5, differed dramatically from the transfer function at the listening position. First, the room gain at low frequencies was substantially less. Second, the cargo area exhibited a different set of peaks and dips in the response. It had four substantial peaks at about 31.5, 63, 200 and 630Hz, of magnitudes 4, 7, 11, and 9dB, respectively. It's interesting to note that first three peaks are in approximate agreement with those predicted in Table 2. The cargo area room gain also had a plateau of about 4dB in magnitude from about 800 to 4,000Hz. The data suggest that sound damping and barrier materials should be used in the cockpit and cargo areas to attenuate the peaks at about 250Hz and 1,600Hz that were evident at the listening position. Bass absorbers, tuned to 31.5 and 63Hz, and panel absorbers, tuned to 205 and 630Hz, may also be necessary for the cargo area.

Figure 6. Untreated cargo area.

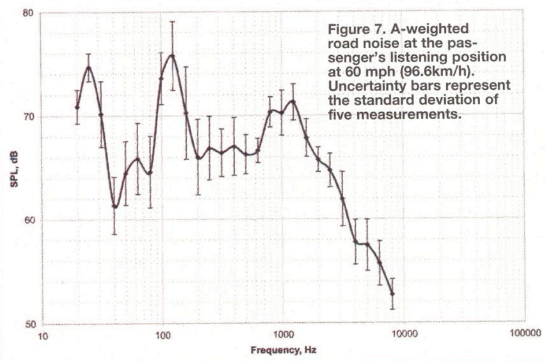


Figure 7. A-weighted road noise at the passenger's listening position at 60 mph (96.6km/h). Uncertainty bars represent the standard deviation of five measurements.

Determining Road Noise

Road noise inside the Sprinter was considerable because the cargo area was completely bare, consisting only of untreated steel structural members and body panels (see Figure 6). In addition, the cockpit area headliner and the A- and B-pillar panels were removed. It was of the utmost importance to determine the road noise spectrum to aid in the selection of appropriate damping and barrier materials.

Road noise inside the Sprinter at the passenger's listening position, which was believed to be identical to the road noise at the driver's listening position because of symmetry, was determined while the vehicle was driven on a freeway at a speed of 60 mph (96.6km/h). The PAA2 was programmed to record sound using A-weighting, the 50 to 110dB measurement range, and a 250ms response time. While an assistant drove the Sprinter, five measurements were taken at the passenger's listening position. The mean SPL was calculated for each of the 31 frequency bands.

The overall A-weighted road noise was 82.7 ± 2.3dB. Figure 7 shows a graph of the A-weighted frequency spectrum of road noise. Besides the high-overall road noise, two large peaks, each about 75dB in absolute magnitude, were evident at 25 and 125Hz. A broad plateau in the road noise of about 70dB in absolute magnitude also occurred from 800 to 2,000Hz. (See Figure 7)

Figure 8. Cascade Audio's VMAX applied to cargo area walls.

The Sound Dampening Process

For sound damping and barrier materials, I chose from Cascade Audio Engineering's line of finely engineered products. As a polymer scientist who specializes in the field of viscoelasticity, I believe Cascade Audio offers a unique and appropriately broad array of products, each specifically tailored to give the highest performance. I consider Cascade Audio's products essential to the sonic performance of my audio system.

The interior sheetmetal surfaces were treated with VMAX, a sound-damping pad constructed from an advanced, non-curing butylene rubber bonded to a thin layer of black aluminum. VMAX possesses exceptional damping properties and is easy to cut and apply. The entire treatment of the cargo area, for instance, was completed in one afternoon. The application of VMAX was intended to damp sheetmetal resonances at 200Hz and above. Figure 8 shows the cargo area of the Sprinter after VMAX was applied. Note that the floor was intentionally not treated at this point in the fabrication process because significantly more work inside the van will be required. Treating the cargo area floor with sound damping materials and barriers will logically take place after much of the cargo area interior is completed. In another article, we'll cover how VMAX was applied to other areas of the van such as the fire wall, dash, A-pillars, cockpit floorboards, doors, and driver- and passenger-side foot wells. (See Figure 8)

Figure 9. Application of Cascade Audio's Acoustical Cotton using heavy-duty construction adhesive (ICI Paints' Liquid Nails PN LN-903) was used to bond the Acoustical Cotton to the VMAX.

Cascade Audio's Acoustical Cotton Composite ("Cotton Composite") was applied over the VMAX to function as a broad-spectrum sound absorber and barrier. The Cotton Composite, with its dense inner barrier layer, and its foil covering provides thermal insulation, sound damping, and sound blocking in one product. I believed the Cotton Composite was the ideal complement to the VMAX since it has an NRC (Noise Reduction Coefficient) of 0.53 at 250Hz, and essentially 0.98 or higher, at 500, 1,000, 2,000, and 4,000Hz. The Cotton Composite, available in 2-foot (609.6mm) by 4-foot (1219.2mm) panels, was easily cut with a utility knife and adhered to the VMAX or the sheetmetal substrate using heavy-duty construction adhesive (for example, ICI Paints' Liquid Nails PN LN-903) as shown in Figure 9. Figure 10 shows the interior cargo area of the Sprinter after the addition of the Cotton Composite. (See Figures 9 and 10)

Although the cargo area floor of the Sprinter hasn't yet been treated, the improvement in the acoustical environment of the van and the reduction in road noise were remarkable. In fact, recording engineers and acoustics engineers who've listened to my van have complimented its acoustics. I hope that this article, in conjunction with Part 1, has conveyed the importance of the listening room, the automotive interior in this case, and its dramatic impact on the sonic performance of an audio system. Stay tuned for Part 3 and beyond, where I'll explain the system design goals, component selection, and show detailed fabrication processes.

Figure 10. Cargo area after application of Cascade Audio's Acoustical Cotton Composite. The seams were sealed with aluminum foil tape.

Resources

1. R. Harley, The Complete Guide to High-end Audio, 1st Ed., Acapella Publishing, p. 94, 1994.
2. R. Harley, The Complete Guide to High-end Audio, 1st Ed., Acapella Publishing, pp. 97-8, 1994.
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4. V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., Audio Amateur Press, 2000, pp. 166-171.
5. R. Harley, The Complete Guide to High-End Audio, 1st Ed., Acapella Publishing, 1994, pp. 207-216.
6. P. R. Bevington, Data Reduction and Error Analysis for the Physical Sciences, McGraw-Hill, pp. 60-1, 1969.