The Car Audio System Nobody Would Build

part 6

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Last month, part five introduced a few important concepts in materials science and mechanical design, and their correlation to improved audio system design and implementation. It also showed the steps of fabrication for the overhead electronics console. This article will focus on the design considerations for, and fabrication process of, the front monitors.

Frequency Hz	Wavelength, λ m (inch)
20	17.3 (680)
40	8.63 (340)
100	3.45 (136)
200	1.73 (68.0)
300	1.15 (45.3)
2k	0.173 (6.80)
20k	0.0173 (0.680)

Table 1. Wavelengths of selected frequencies.

Design Considerations

Before discussing the choices that were made in designing and building the front monitors, it's important to consider certain principles of loudspeaker transducer performance and mid- and high-frequency loudspeaker enclosure design considerations.

When designing an automobile audio system, it's important to know the relationship between the frequency and wavelength of sound. How sound behaves in an automotive environment is largely influenced by its wavelength. For example, mechanisms affecting sound such as absorption, diffusion, and reflection of sound are dependent upon its wavelength. For instance, sound is reflected from objects that are large relative to the wavelength of the impinging sound. Sound behaves like "waves" below about 300 to 400Hz, and like "rays" above 300 to 400Hz.[1] **Table 1** shows the relationship between frequency and wavelength.

The radiation pattern of sound produced by a loudspeaker transducer narrows as the frequency increases. **Figure 1** shows the -6dB off-axis points for loudspeakers of various diameters at various frequencies. Of particular importance is the line corresponding to the "1-inch speaker," which is representative of a tweeter's dispersion. At 10kHz, the sound from a typical tweeter is already diminished 6dB at a point about 80° off-axis. The radiation pattern continues to narrow as the frequency increases until the output is diminished by 6dB only 40° off-axis at 20kHz. Clearly, this rapid narrowing of dispersion with increasing frequency must be taken into consideration when locating and aiming the tweeter in order to maintain adequate frequency response.

(See Figure 1)

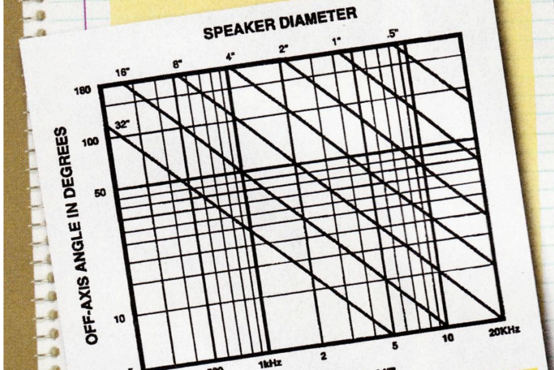


Figure 1. Loudspeaker dispersion properties. Lines indicate -6dB off-axis points. Reprinted from V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., p. 8, 2000.

The radiation pattern of a midrange or woofer transducer also affects the choice of upper crossover limit. At the crossover frequency between the midrange and the tweeter, the tweeter's horizontal polar dispersion is wide, relatively speaking, and that of the midrange is beginning to narrow. This can lead to non-uniformities in the horizontal polar dispersion at certain frequencies in the transition region from the midrange to the tweeter. Measurements have confirmed that irregularities in this transitional region can adversely affect stereo imaging. **Figure 2** shows how the off-axis output of a transducer diminishes relative to the on-axis output. **Table 2** provides recommended upper crossover frequencies for woofers and midranges of various diameters. Obviously, the criterion associated with -3dB attenuation at 45° off-axis is more stringent and may lead to better integration between the midrange and the tweeter at the crossover frequency.

Transducer Diameter inches	Frequency, Hz -3dB at 45°off-axis	-6dB at 45° off-axis
15	661	1,043
12	912	1,427
10	1,065	1,674
8	1,302	2,055
7	1,540	2,421
5	2,051	3,229
4	2,687	4,238

Table 2. Recommended upper limit for lowpass crossover frequency.[2]

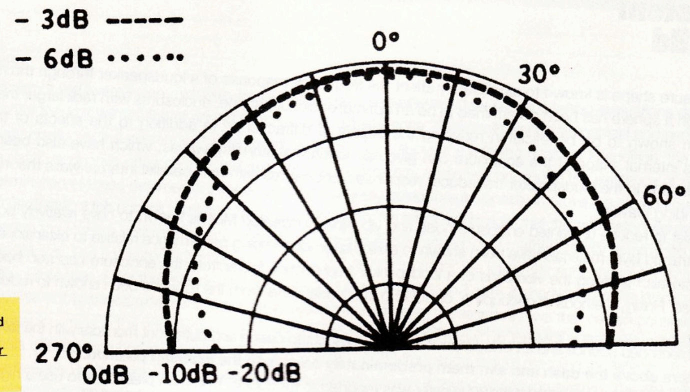


Figure 2. Horizontal polar response for midranges and woofers. Reprinted from V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., p. 105, 2000.

Although it's theoretically desirable to have a loudspeaker radiate all frequencies from a single point, the vast majority of loudspeaker systems, especially those in automobile audio systems, rely upon individual, non-coincident loudspeaker transducers each radiating different frequencies. As a consequence, each loudspeaker transducer is separated both horizontally and vertically **(see Figure 3).** Vertical separation gives rise to a phenomenon called "lobing," the consequence of inter-transducer interference patterns, which result in a severely non-uniform vertical polar response. The extent of lobing worsens with greater vertical separation, as shown in **Figure 4.** The obvious solution is to minimize the vertical separation of the loudspeaker transducers as much as possible, or use a high-quality coaxial loudspeaker transducer.

Horizontal driver separation is virtually inevitable in automotive audio systems for two reasons. First, the geometrical configuration of the automobile interior limits the available mounting locations for the individual loudspeaker transducers. Second, unintentional horizontal separation may result if care isn't taken to align the loudspeaker transducers' acoustic centers. Although the exact determination of a loudspeaker transducer's acoustic center involves sophisticated equipment and complex measurement techniques, a useful approximation of the acoustic center lies at the center of the voice coil.[3] The task of aligning the acoustic centers is further compounded by the fact that the acoustic center of a loudspeaker changes with frequency as shown in **Figure 5**. Improper horizontal alignment of loudspeaker transducers can lead to an unintentional tilting of the vertical polar radiation pattern and phase errors. If it's not possible to physically align the loudspeaker transducers' acoustic centers, appropriate inter-transducer time delays have shown to be equally effective.[4]

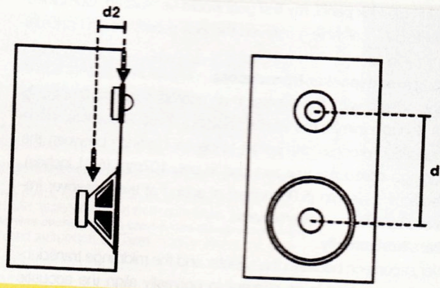


Figure 3. Vertical (d1) and horizontal (d2) separation of loudspeaker transducers. Reprinted from V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., p. 107, 2000.

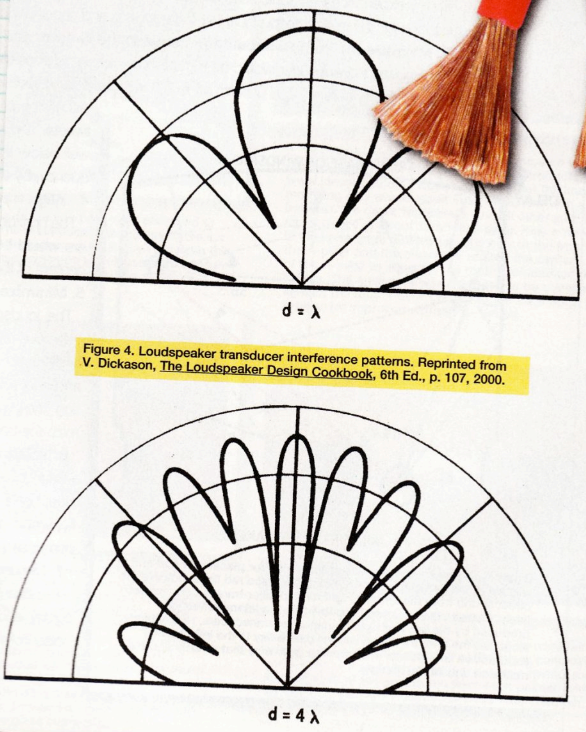


Figure 4. Loudspeaker transducer interference patterns. Reprinted from V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., p. 107, 2000.

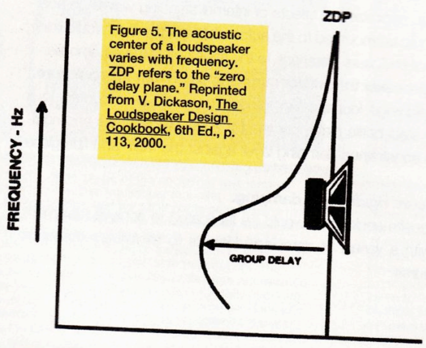


Figure 5. The acoustic center of a loudspeaker varies with frequency. ZDP refers to the "zero delay plane." Reprinted from V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., p. 113, 2000.

Loudspeaker enclosure shape is known to significantly affect the frequency response of a loudspeaker through the mechanism of diffraction. Although a sphere has been determined to be an optimal enclosure shape, enclosures with radii larger than 50.8mm (2 inches) have been shown to be beneficial in reducing the effects of diffraction.[5,6] In addition to the effects of the external enclosure shape, the internal shape of the enclosure can give rise to internal standing waves, which have also been shown to cause amplitude variations in the loudspeaker transducer response.[7] Enclosures with non-parallel internal walls theoretically help to distribute the standing waves.

Several methods exist to reduce unwanted enclosure noise and vibrations. Untreated MDF is known to have relatively poor damping characteristics. Constrained layer materials have been shown to exhibit superior damping performance relative to extensional (externally-applied) damping materials.[8] Isolating the vibrations of a loudspeaker transducer's frame from the enclosure has also been shown to reduce enclosure noise. Finally, methods of decoupling, or isolating, the loudspeaker from the floor has been shown to reduce interfering floor vibrations.[9]

Based on the aforementioned science and art of loudspeaker design, I set out to design and build front monitors with the following goals:

1. Mount the tweeters above the dash and aim them predominately on-axis to the listening position.

In part three, the resonant frequency of the MD130 tweeter was reported to be 850Hz. Common practice is to use a highpass crossover frequency approximately one to two octaves above the resonant frequency. The lowest reasonable highpass crossover frequency was expected to be between 1,700 and 2,550Hz. Because the tweeter was expected to potentially operate between the frequencies of 1,700Hz and 20kHz, any objects in the path between the tweeter and the listener between 0.203m (6.69 inches) and 0.017m (0.68 inch) in size would interfere with the output of the tweeter. Combined with the fact that tweeters nominally 1-inch in diameter have significantly narrowed dispersion as the frequency increases, it seemed logical to mount the tweeter above the dash aimed nearly on-axis. Conversely, if the tweeter were aimed substantially off-axis, not only would it suffer from reduced output, but also from "comb filtering" as a result of early reflections off surfaces, such as the dash, windshield, center console, or A-pillar.

2. Mount the midranges above the dash and aim them identically to the tweeters.

In part three, it was determined that the resonant frequency of the MW150 loudspeaker transducer in an appropriate sealed enclosure was about 95Hz. Common practice is to use a highpass crossover frequency approximately one to two octaves above the resonant frequency. Therefore, each MW150 would likely be tuned to play from 200Hz to as high as 2,687Hz (from **Table 2**). The wavelength of sound corresponding to these frequencies is 1.73m (68.11 inches) and 0.128m (5.06 inches), respectively. If the midrange transducers were located above the dash, objects between the path of loudspeaker transducer and the listener, capable of causing reflection, absorption, or diffusion, would be avoided.

An additional benefit of locating the tweeters and midranges above the dash was that no objects were between the loudspeakers to degrade the stereo image. Conversely, if the midrange loudspeaker transducers were mounted in the kick panels, a practice commonly believed to provide optimum results based on minimal pathlength differences between left and right channels, they would be subject to significant reflection, absorption, and diffusion by the listener's body before the sound was able to reach the listener's ears. Placing the midrange transducers in the kick panels also violates the desirable goal of placing the midrange as close as possible to the tweeter to minimize lobing. If the tweeter were placed close to the midrange transducer in the kick panel, my first goal would be violated. Combined with my experience that sonic sources playing frequencies greater than 100Hz are localizable, I believed the kick panels weren't optimal locations for the midrange loudspeaker transducers, and especially not the tweeters.

3. Minimize the vertical separation between the tweeter and midrange loudspeaker transducers.

The midrange transducer would be mounted as closely as possible to, and on-axis with, the tweeter in an attempt to achieve not only point-source coherency and uniform off-axis horizontal polar dispersion, but also to minimize the effects of lobing. As you'll see later in the discussion of the fabrication process, the center-to-center distance between the tweeter and the midrange transducer was reduced to only 107mm (4.21 inches), well below the expected wavelength (5.06 inches) of sound at the crossover frequency, by the use of a special mounting scheme.

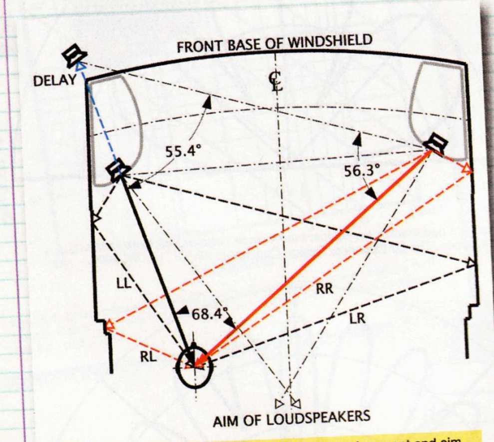


Figure 6. Geometry of cockpit and front monitor placement and aim relative to the listening position. Solid black and red lines indicate the direct sound from the left and right loudspeaker transducers, respectively. Dotted black and red lines indicate the lateral reflections produced by the left and right loudspeaker transducers, respectively. Note that the introduction of proper time delay in the left channel (blue dotted line) results in a listening geometry that closely approximates an equilateral triangle.

4. Align transducers horizontally.

The horizontal driver separation between the tweeter and the midrange transducers would be physically minimized in an attempt to optimally align the acoustic centers of the transducers.

5. Minimize diffraction.

The loudspeaker enclosures would be fabricated with smooth contours and generous radii, greater than 50.8mm (2 inches) on all sides, to minimize the effects of diffraction. The internal shape of the enclosures would consist entirely of curved and non-parallel walls to minimize the effects of internal standing waves. In addition, the enclosures would be mounted to the automobile in ways that would minimize the transmission of enclosure vibrations to the structure of the automobile.

6. Isolate a rigid loudspeaker transducer mounting plate from the enclosure.

Each tweeter and midrange loudspeaker transducer would be mounted to a steel baffle plate. The steel baffle plate, chosen for its favorable mass and rigidity, would sandwich a constrained damping layer against the MDF and fiberglass composite enclosure.

7. Maximize enclosure rigidity and damping.

The fiberglass composite enclosures would be fabricated to achieve maximum rigidity and treated with a variety of damping materials to minimize extraneous noise from the enclosures.

8. Optimize imaging.

The placement and aim of the tweeter and midrange transducers would be determined by critical listening evaluations designed to arrive at the best balance between soundstage width, center focus, minimization of early reflections, and tonal balance. The ideally sloped windshield and headliner in the cockpit of the Dodge (Mercedes-built) Sprinter essentially precluded the existence of detrimental reflections from above the listening position. In addition, the high placement of the monitors above and at the front edge of the dash, along with other geometrical and physical parameters, essentially precluded the existence of detrimental reflections from below the listening position. The virtual elimination of these detrimental vertical reflections was expected to substantially improve the stereo imaging.

Figure 6 shows the geometry of the cockpit relative to the listening position. It's important to note that this geometry was measured and documented only after hundreds of hours of critical listening to establish optimal imaging. Lines of direct and reflected sound were mathematically determined and illustrated in **Figure 6**. The nomenclature for the reflections is as follows. The first letter indicates the source of the reflection, either the left or the right channel, indicted by an *L* or an *R*, respectively. The second letter indicates the side of reflection, *L* for the left side and *R* for the right side. The data in **Table 3** characterizes the lateral reflections illustrated in **Figure 6**.

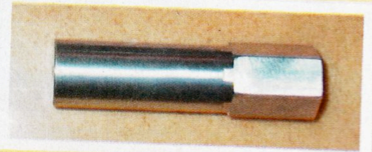
It's important to note that not all lateral reflections are deleterious to stereo imaging. Research shows that certain controlled lateral reflections can actually improve the imaging and sense of spaciousness in the soundstage.[10] For example, the *LR* reflection shown in **Table 3** is expected to be diminished by at least 10dB, perhaps more if one considers the effects of narrowing horizontal polar dispersion with increasing frequency, before reaching the listener. This reflection was thought to be negligible. The *RL* reflection, luckily, strikes the B-pillar trim piece and will eventually be treated with a sound-absorbing system. The *RR* reflection emerges from the monitor at an angle 108.9° off-axis, so its magnitude will be substantially reduced at higher frequencies. **Table 3** also provides predictions for the periodicity of "comb filter" effects.

Path	Distance mm	Delay t ms	1st Null 1/(2t) Hz	Null spacing 1/t Hz	Reflection level dB	Direction off-axis °
Direct from left loudspeaker	937	n/a	n/a	n/a	n/a	16.8
Direct from right loudspeaker	1472	n/a	n/a	n/a	n/a	16.2
LL	1060	0.356	1,404	2,808	-1.07	69.0
LR	3036	6.08	82.2	164	-10.2	38.4
RL	2147	1.96	255	510	-3.28	13.8
RR	1754	0.817	612	1224	-1.52	108.9

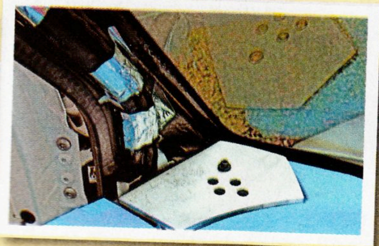
Table 3. Characterization of lateral reflections

Fabrication of the Dash-Mounted Monitors

The front monitors took almost a year to design, fabricate, optimize, and finish. The following figures illustrate the fabrication process of the monitors.

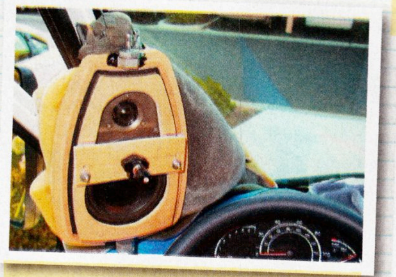


1. Two posts, containing internally threaded M5 holes on each end, were machined from aluminum. Each of these posts was anchored to a steel cross-member below the dash and supported the base monitor above the dash.

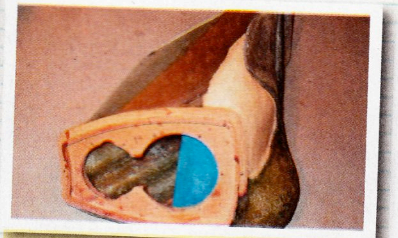


2. View of the driver-side binding post plate anchored to its supporting post. The plate doesn't touch any of the surrounding surfaces. A Sorbothane gasket goes between this plate and the fiberglass enclosure to help isolate enclosure vibrations from the automobile's supporting structure.

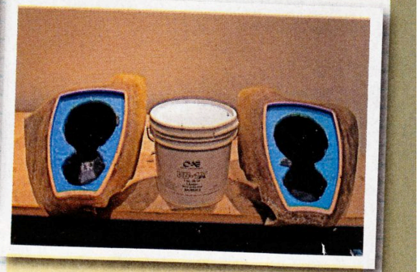
3. The initial shape of the monitor's enclosure was formed using Klean Klay (Art Chemical Products, visit www.kleanklay.com). Notice the constant thickness of modeling clay would result in an enclosure with a gap between the dash, windshield, and all other surrounding surfaces of about 13mm (0.5 inch). Also noteworthy is the knife-edge molded into the clay at the front of the A-pillar and the clearance around the centerline of the A-pillar to allow for the routing of loudspeaker cables. The enclosure was designed to be clamped against the rubber door gasket on the back edge of the A-pillar for improved vibration isolation.



4. Once the basic shape of the enclosure was formed, the steel loudspeaker transducer mounting plate, the Sorbothane gasket, and the MDF baffle plate were mounted and carefully aimed. A magnetically attached MDF jig held a laser gun site exactly between, and on-axis with, the two loudspeaker transducers to assist in precisely aiming the loudspeaker transducers. The acoustic foam stuffed behind the baffle plate represented an attempt to reduce dipolar radiation. Literally hundreds of hours were dedicated to critical listening sessions and frequency response measurements to optimize the aim of the loudspeakers for optimal balance between soundstage width, center focus, minimization of early reflections, and tonal balance.



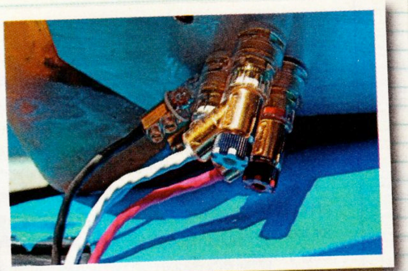
5. Once the optimum aim of the front baffle was determined, Klean Klay was used to create molds for portions of the enclosure walls. After about four campaigns of moid creation and fiberglass composite lay-up, the enclosure was complete. Notice the incorporation of Cascade Audio's VB-FD into the walls of the enclosure to provide them with internal damping. Care must be taken to remove the residue left by the Klean Klay mold. Multiple wipe downs with rags soaked with acetone, followed by sanding with 36-grit sandpaper, followed by additional wipe downs, provided an ideal substrate for additional layers of fiberglass composite.



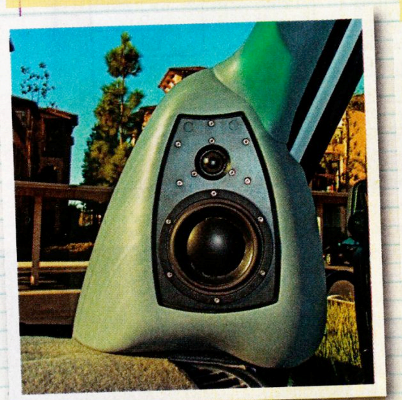
6. After the internal walls and the MDF baffle were reinforced with substantial amounts of fiberglass composite composed of both chopped mat and woven roving, the internal walls of the enclosures were each painted with six coats of Cascade Audio's VB-1X vibration damper.

7. The exterior of each of the enclosures was contoured with substantial amounts of fiberglass composite comprised of chopped mat. Final shaping was done using Evercoat's Tiger Hair fiberglass-reinforced filler and Rage Gold body filler. The final wall thickness of the fiberglass composite enclosure varied from 15 to 32mm (0.591 to 1.26 inches). The largest possible pieces were cut from Cascade Audio's Deflex PowerPads and adhesively bonded to the inside of the enclosure.

8. Klean Klay was sculpted to create molds for the A-pillar trim pieces. The front edge of each trim piece was knife-edge shaped to properly rest in the damped v-groove at the front of the A-pillar, and the rear edge of the trim piece rested against the rubber door gasket for improved isolation. The trim piece was clamped tightly against the A-pillar to resist rattling and vibration using one counter-sunk M4 socket head cap screw (see Figure 16).

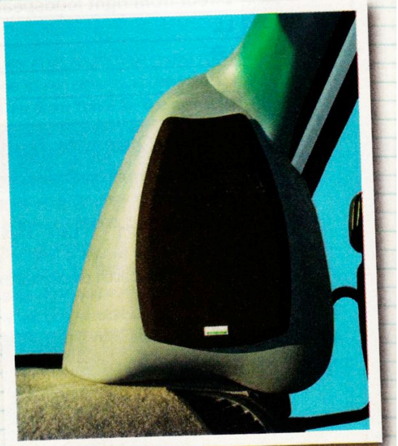


9. A combination of binding posts, spade lugs, and angled banana plugs, all from WBT (see www.wbtusa.com) were used to connect the loudspeaker cables to the monitor. This cluster of connections fit below the dash in a cutout originally designed for the OEM loudspeaker. Loudspeaker cables were Kimber Kable's 4TC (see www.kimber.com). The red and white colored conductors correspond to the tweeter's positive and negative terminals, while the blue and black colored conductors correspond to the midrange's positive and negative terminals.



10. View of the completed passenger-side front monitor. The loudspeaker grille is removed to reveal the details of construction. The front-mounting baffle plate was CNC-machined from 6.35mm (¼-inch) thick steel and coated with a black oxide treatment. To better align the acoustic centers of the loudspeaker transducers, Dynaudio's MD130 tweeter was mounted behind the plate, while Dynaudio's MW150 was mounted in front of the plate. All of the M4 stainless steel low-head socket head cap screws were recessed into counterbores to minimize diffraction. The screws secure the steel baffle plate to a constrained layer damping material placed between the plate and the enclosure. The steel baffle is recessed into the enclosure to provide a smooth transition from the plate to the contours of the enclosure, all of which possess radii greater than 50.8mm (2 inches) to minimize the effects of diffraction. The improvement in soundstage imaging due to properly contouring the monitors was simply stunning. The wall thickness of the fiberglass composite enclosure varied from 15 to 32mm (0.591 and 1.26 inches), and weighed in excess of 106 N (24 pounds) each.

11. Speaker grilles were fabricated from 9mm (0.354 inch) marine plywood and perforated-steel sheet, which had an open area of 79 percent. The perforated steel was adhesively bonded to the marine plywood, which had generously beveled edges. Cylindrical rare earth magnets, adhesively bonded to the back of each speaker grille, allowed the grilles to be readily attached or detached from the monitors without tools. The grilles were covered with black grille cloth and a small Dynaudio logo was bonded to the lower front edge of each speaker grille. The grilles were designed mainly to protect the loudspeaker transducers from damage and should be removed for critical listening sessions.



12. View of the completed passenger-side front monitor with the loudspeaker grille magnetically attached.

Image is Everything

Many of you may question the rather analytical approach I took in building the front monitors, apparently giving less importance to aesthetics. Some will question whether the visibility out of the van was compromised. I can assure you that plenty of visibility still remains. Still, others would think the front monitors are simply ugly, too "in your face," and would not have them in any car regardless of how they sounded. Ben Oh's "Driver's Seat" column in the Aug. '08 issue of *CA&E* titled, "Car or Audio," addresses this topic brilliantly. And lest you think I'm crazy, I agree with most of you that the monitors I fabricated in this article are rather imposing and bulbous. But wait until you hear how they sound; I think you'll be floored. Recently, I attended, exhibited, and demonstrated at Mr. Marv's barbecue.[11] At the barbecue, I met a person who was captivated by my obsession for fine craftsmanship and the sound of my system. As I explained the choices I made during the creation of an audio system dedicated purely to serving the music, I poked fun at the whole cargo van idea and especially the stamped-steel wheels. I laughed when I said I could've purchased a very expensive Bimmer with the money I used to build my van. His reply was, "With sound like you have, I'd take your van any day!" I really liked that guy. Finally, I'd like to acknowledge and thank renowned audio component designer Steve McCormack for contributing his expertise and guidance during the loudspeaker transducer placement and aiming process. Please stay tuned for Part 7, where I'll continue the fabrication process with the door-mounted woofer enclosures. ○

Resources

1. F. A. Everest, The Master Handbook of Acoustics, 4th Ed., **McGraw-Hill**, p. 236, 2001.
2. V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., **Audio Amateur Press**, p. 105, 2000.
3. V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., **Audio Amateur Press**, p. 113, 2000.
4. V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., **Audio Amateur Press**, p. 112-116, 2000.
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7. V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., **Audio Amateur Press**, p. 100, 2000.
8. V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., **Audio Amateur Press**, p. 101, 2000.
9. V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., **Audio Amateur Press**, p. 102, 2000.
10. F. A. Everest, The Master Handbook of Acoustics, 4th Ed., **McGraw-Hill**, pp. 409-414, 2001.
11. See http://community-2.webtv.net/MarvsPlace/MarvsPlace/index.html