Concepts and Considerations in Speaker System Design for Small Scale Model Trains: a Technical White Paper

By jt burke of Scale Sound Systems August 2018

Background

For the past 3 years, I have been working to provide better sounding systems for both my own locomotives and for the DCC-Sound installations I am commissioned to perform for clients. I wanted a broader frequency range (deeper low frequencies, clearer high frequencies) a smoother frequency response (no sharp, resonant peaks) and a detailed sound (better transient response). When I set out on this journey, I had little idea as to what types and sizes of drivers would yield the best performance and to what degree enclosure design would have on the final sound. I also learned that the specification sheets provided for these drivers was worth about as much as a snow ball is to an eskimo. In my professional audio work, I am accustomed to spec sheets heavily influenced by the marketing department, but good heavens, some of these spec sheets presented numbers that possessed no information of any value at all!

Case in point; one driver's spec states the frequency response as 300Hz-20KHz. However, digging a little deeper for a manufacturer-supplied response graph showed the response was fairly linear between 1.8KHz and 4KHz, with a nice presence boost around 5.8KHz and rolling back down to 8.5KHz. Not bad, until you realize that going down in frequency from 1.8KHz, the response is 25dB-down in amplitude at 1KHz and 50dB down at 300Hz! You can make any driver reproduce 300Hz, but to produce it at a usable output is another matter. The real world free-space response of this driver is about 1.2KHz to 20KHz.

Another thing I learned is that many of the design ideas utilized in professional audio do not adapt well with such unique driver designs and on such a small scale.

I will say it upfront; if all you want is louder locomotive sound, there are plenty of ways to get there. This paper will detail the processes of achieving *higher fidelity* locomotive sound.

A quick note about my nomenclature. A "driver" is the raw-frame speaker, or transducer. A "speaker" is the complete assembly, driver+enclosure. LF, MF and HF all mean "low frequencies, mid frequencies and high frequencies". Understand that a "flat response" is not the same as a "smooth response". A flat response shows no deviation in amplitude across a range of frequencies. A smooth response means that any changes in amplitude happen gradually, which sounds good, as opposed to sharp peaks or notches, which sound bad. "SSS" is sometimes used to abbreviate "Scale Sound Systems".

Choosing Drivers

After evaluating about a dozen traditional cone drivers of various size, design and make, I quickly realized that low profile micro speakers, as they are known in the industry but are commonly referred to as "sugar cubes" among model railroaders, yielded a much more linear response with faster transients than traditional cone miniature drivers could produce. Their efficiency, particularly below 1KHz, was astounding for their size. The only significant tradeoff was lower power-handling, but since I was after better sound, not louder sound, I could accept this.

Of course, this meant buying and evaluating every single 13x18 driver that was then available on the market. Since that time, I have and continue to buy every new 13x18 driver that is introduced to the market, comparing it to the model I use in my designs. I will also occasionally buy small drivers of other design types. To date, nothing has compared to the driver I chose 3 years ago. It is long out of production and I bought all of the remaining stock. Once it is depleted, I will have to sort something out!

I do use sizes of 8x12, 8x15 and 9x16 for my N scale installations. There have been very, very few 8x12 and 8x15 models available and only one of each size that is still available (from Soberton) that I can regularly find. Fortunately, they sound pretty good! As for 11x15s, this size has been relegated to those N scale installations that can accommodate them. I have yet to see any benefit from, or any installation that requires, using this size in HO. Thus, I use a 13x18 for all of my HO designs to date.

Characteristics of Low Profile Micro Speakers

These drivers utilize a flat backplate with a large, rectangular central magnet that would be the pole piece of a traditional driver. Surrounding this magnet is the driver's voice coil. Two long, skinny magnets run the length of the frame outside the VC. The ends are simply the frame itself. This space forms the voice coil gap. The VC gap is much wider than traditionally seen in cone drivers. There is no spider at all; the only diaphragm suspension is the surround. The back plate is vented, either by small, circular ports, long slots or a combination of the two. Interestingly, taking raw-frame/free-space, swept-sine measurements with 700mW applied @ 10cm, the amplitude and frequency response is almost 100% identical when measured from the front or back of the driver. The backside reading does show that the presence peak is slightly higher and narrower, but this is the only deviance measured between the front and back. By design, these low profile drivers are intended to fire into an enclosure, with the backplate facing out. This provides the ideal acoustic suspension to dampen the diaphragm, which improves the transient response, lowers distortion and permits greater power input. More importantly, the backplate is key to the driver's mid-high frequency response. Even though the front/back response and amplitude are near identical with raw-frame/free-space measurements, once mounted to an enclosure, the difference between diaphragm facing in verses facing out is night and day. If using these drivers diaphragm facing out, the dimension of the enclosure will have a profound impact on the mid-high frequency response, causing severe internal reflection-induced comb filtering that devastates the mid-high response. If you have a speaker with the diaphragm facing out and it sounds better than facing in (correctly and accurately compared, documented and evaluated), it was purely by luck and the results will not be repeatable when using differently sized enclosures. Furthermore, the locomotive's shell provides additional HF diffusion and attenuation, only confounding the tempered HF response of the facing out configuration. Of course, if your driver has an overly piercing mid-high output, the facing out configuration, in some instances, may serve you well at smoothing the driver's overall response.

I've prepared a video demonstrating the difference in sound when facing the diaphragm in or out. Both drivers are mounted in the same size and style of enclosure, measuring 14mmH x 18mmW x 52mmL. Both the internal volume and external dimensions are closely matched, a critical consideration when comparing how two different speakers will perform within a given space.

Shown here are the response graphs of the systems under comparison, 100Hz-20KHz swept-sine, 700mW applied @ 10cm.



Diaphragm Facing IN

Diaphragm Facing OUT

As can be seen, diaphragm facing IN provides a smooth and clear mid-high response. Diaphragm facing OUT indicates a very uneven mid-high response that is quite subdued. *The mid-low response is the same*.

Here is the unlisted Youtube link to hear the difference. Both systems are fed via Loksound Select, file #73408, an EMD 16-645E3 (as found in GP/SD40s).

https://youtu.be/wBUy1XqK1SU

Page 3: Concepts and Considerations in Speaker System Design, Scale Sound Systems 2018

Enclosure Considerations

Enclosure size, or internal volume, is what most people consider when designing a box for a driver. Obviously, overall size is subject to the space we have available in the locomotive. In professional audio, everything about the box has an impact on its performance. Large drivers displace a lot of air pressure. Surprisingly, I found differences, some subtle and some drastic, with micro speaker systems as well!

Material type changes the sound. Styrene, ABS, PLA, PETG, all of them exhibit slightly different tonal characteristics. I will still experiment with materials every now and then. Some of the recent "wood" filaments that use 20-40% wood fiber might be *nifty*. But nifty, while novel, could simply be awful!

Enclosure wall thickness changes the sound. Too thin, and LF is reduced while all kinds of higher pitched resonances will ring, with the thin walls acting like high frequency exciters. Too thick and the system is attenuated in resonance, reducing the warm, low-mid output, while yielding a bit more mid/high definition. Bracing can be used to good effect, which reacts differently than simply making the bottom or sides thicker.

The *baffle* is the part of the enclosure that supports the driver. It would be the front "face", or panel, the speakers and tweeters are mounted to on your home stereo. Baffle thickness changes the sound. Too thin and the driver couples poorly to the enclosure, LF output is reduced and distortion goes up.

In speaker design, there is a popular belief that enclosure resonance is the enemy. Indeed in the context of critical-listening to music or similar, excessive enclosure coloration could easily ruin the experience. However, the reality is that every speaker system exhibits enclosure resonance to some degree, and every driver has its own "sound" to begin-with. (A driver with "linear frequency response" does not exist!).

Of the common enclosure resonances encountered, low-frequency resonance is much more acceptable to the ear than higher pitched resonance, where our ears are more sensitive. Both the presence of enclosure resonance and the many different attempts to reduce it, when not implemented properly, can indeed be destructive to the speaker's overall performance. As an example, simply adding more-mass to the enclosure in an attempt to dampen the resonance will actually reduce the desirable low-frequency resonance, and shift the resonant frequencies higher! (This is not what we are seeking, we want our prime movers to rumble, not whistle!)

However, real-world speaker system design is a dance of mating an imperfect driver to an imperfect enclosure and balancing the resonances so that the union forms a happy marriage. The best example cases reconcile this challenge by using carefully-planned resonance behaviours to achieve a desired result.

The use of internal absorption to control resonance has been studied and applied with varying degrees of success. This absorptive material should only be considered *after* the ideal enclosure design has been tested and chosen. In professional audio, this method is generally a means of limiting the higher-pitched resonances. There simply isn't enough mass to the absorptive material to have a significant impact at the lower frequencies. To date, my own research of the matter as it applies to on-board sound is ongoing. I presently do not have enough conclusive data gathered to form an official opinion.

Now simply slapping a driver onto the biggest box you can fit will only get you so far. Like any driver, these low profile micro drivers have a limit as to how much air they can displace and as such, how much SPL they can produce at a given *frequency range*. I emphasize frequency range because we are interested in what a speaker can do broad-band (lows-mids-highs), not what it can produce in a narrow window of frequencies. It's important to understand that a large or fancy enclosure will not produce more bass. The driver must be capable of producing the desired frequency range at usable levels. But a well-designed enclosure will balance the acoustic impedance around the driver's resonance. This is where air compliance and driver compliance really come into play.

Most 13x18 drivers are designed for enclosure volumes of anywhere between five cubic centimeters and maybe ten cubic centimeters, depending on the model. Increasing the enclosure volume will allow the low frequency response to extend (*if* the driver is able to produce it at usable levels) until it becomes so large, the LF response begins to taper back off and the driver isn't even aware that it's attached to an enclosure anymore. We don't usually have that much room in HO! However, as the internal volume increases, the response begins to balance out between the lows, mids and highs until at one point, the LF/MF starts to mask the HF. Increased low frequency power, balanced midrange and smooth highs are what we're after, but when the sound becomes murky and wooly, we're simply trading one type of bad audio for another. A loss of total SPL output also comes into play as the box grows larger. Adding to this response shift and SPL loss, the sound waves within the enclosure have more room to move around, interact and wreak all kinds of modal anomalies.

This is where Scale Sound Systems Diapasonic Voicing[™] comes into play. I create places for the internal waves to go instead of just colliding together, allowing the lower frequencies to accurately develop and resonate, clearing the midrange of excess resonance and tuning the upper-mid/high response so that the larger enclosures, which provide great bass, still have mid/high clarity, detail and output. If a certain sound has a somewhat anemic mid-range, I'm able to give it some throaty growl with these techniques as well. After doing this so much, I have learned some degree of predictability with these internal designs, though in many cases, it's still a lot of design-listen-measure, design-listen-measure, sometimes going through a half dozen or more designs before I get what I'm looking for in a single model.

I have concluded that, given the small enclosure sizes of HO scale trains, sealed enclosures provide the ideal response. Applying ideas and concepts from my use of pro audio systems, I have tried about every practical concept I can think of; various ported and vented enclosures all tuned differently, bandpass systems, folded-horn loaded designs, vented transmission lines and other whacky ideas. All of these produced louder midrange (often times very efficiently!) but with drastic reductions in LF and HF reproduction. The idea that an enclosure so small could effectively act in a "bass-reflex" manner simply does not add up. Ported and vented designs require a minimum amount of cubic volume for the internal waves to load (couple) before exiting the enclosure at a tuned resonance low enough to support the LF response. When a ported/vented enclosure is too small, the released air is at too high of a resonance and will emphasize the midrange, not the lower frequencies. Likewise, folded-horn and vented transmission line designs require a minimum compression zone at the driver entrance and overall minimum pathlength of the throat to work effectively with low frequencies and then, at the expense of compromised mid-high response. By contrast, sealed enclosures are able to load down to a lower frequency via optimally aligned, captive acoustic impedance. Even so, there is a limit to how small a sealed enclosure can be, as will be demonstrated in the coupled array segment later.

Wrapping up this section on enclosure design, I will state a quick note about the term "infinite baffle". Some will refer to a sealed enclosure as an "infinite baffle enclosure". *This is not correct*. As noted above, the baffle is the enclosure plane on which the driver is mounted. A true infinite baffle does not place any acoustic suspension on the diaphragm like a sealed enclosure will. Likewise, an infinite baffle does not create any acoustic impedance, which all enclosures use to some degree, to bolster the driver's LF reproduction. An infinite baffle means exactly what it says. It is a singular plane (strait or bent) that extends equally in all directions infinitely. It does not need to extend literally to infinity to all directions in space, but only as far as the driver's LF output is concerned. If the driver's LF output extends to 100Hz, which has a wavelength of about 136" (346cm), the infinite baffle will need to radiate at least 136" from all sides of the driver so that the front and rear sound waves will not destructively cancel each other. *This is the reason why using the locomotive's shell as an infinite baffle will drastically limit the LF potential*.

Evaluating Drivers Today

The 13x18 driver evaluation I am presenting here includes a few models that are active as of this writing and a few that are obsolete, but may still be found. I've tested many more models over the years, but this is a reasonable grouping for today. Listed below are the models in order, from least LF output to most LF output. Noted beside each is its average sensitivity as relevant to the other models. I could have noted the manufacturer's sensitivity rating, but that is not a very useful figure when comparing drivers to one another used within context. The Knowles Sambo has the highest sensitivity of the group and thus is considered unity (zero). If you want the loudest speaker of this group, this is the one. The negative dB reading next to the rest indicates how much quieter they are compared to the Sambo with equal power applied.

Make/Model	Status	Comparative Sensitivity
CUI CMS-181325-078SP	(active)	- 2.6 dB
PUI AS01808MS-SP18-WP-R	(active)	- 3.1 dB
CUI CMS-18138A-SP	(active)	- 1.9 dB
Knowles SAMBO	(obsolete)	0.0 dB (most sensitive)
PUI AS01808AO-3-R	(active)	- 1.9 dB
PUI AS01808AO-WP-R	(active)	- 2.5 dB
Seltech GR1813L025UN8	(active)	- 0.7 dB
Knowles DUMBO	(obsolete)	- 2.1 dB
Scale Sound Systems	(obsolete)	- 3.3 dB

Of course, low frequency output is not the only factor to consider in choosing a speaker, but its what draws most modelers to replacing their speakers in the first place.

Each of these drivers were mounted to my AHGS-GP15-087 enclosures. These enclosures are 10mmH x 18mmW x 33mmL in exterior dimension. I chose this enclosure because 1) it's a somewhat smaller, common size that will fit in a lot of locomotives and 2) it is one of the more simple designs I have and not as specifically voiced as some of the other models.

All of them were fed from the same Loksound Select decoder loaded with file #73408, an EMD 16-645E3, with output running near max. All of them have been level matched within 0.1dB so that an accurate conclusion can be drawn by hearing them all at the same SPL.

Unfortunately, I did not photograph all of the models. Stock photos will be used for all of them except the Scale Sound System example, which is photographed mounted to the AHGS-GP15 enclosure that was used for all of these drivers in this evaluation.

https://youtu.be/U2vOXTI28sM

The first five drivers are quite disappointing. Things start to look up a little with the PUI AS01808AO-WP-R (warm low-mids) and Seltech (strong bass potential) drivers. The Knowles Dumbo has been popular with modelers, as it has a lower self-resonance and more LF potential than the rest, aside from the Scale Sound Systems model. It has a "warm" sound, though I find the midrange and highs to be grainy and smeared-sounding. I heard, then measured, higher harmonic distortion with the Dumbo than the others, which accounts for these artifacts.

Shown here are FFT graphs with the Dumbo and the Scale Sound Systems drivers each receiving continuous 100Hz and 200Hz sine-waves with 700mW applied @ 10cm.



Knowles Dumbo Harmonic Distortion @ 200Hz

Scale Sound Systems Harmonic Distortion @ 200Hz



You will notice that both the Dumbo and SSS drivers have close output at the fundamental frequencies of 100Hz and 200Hz. The SSS driver does show a couple dB more power than the Dumbo. The SSS driver's 2nd, 3rd and 4th harmonics are a touch stronger than the Dumbo. The shocking finding is how much harmonic distortion the Dumbo exhibits at every subsequent harmonic up to 5KHz! The SSS driver shows very little to no perceptible distortion after the 4th harmonic. The harmonic distortion exhibited by the Dumbo accounts for its "warm" sound, but also its lack of conveying clean, clear detail of reproduction.

Since these demonstrations were recorded with the decoder near maximum output, one thing to note is the slight whizzing or crackling sound you may hear when the horn blows through the SSS driver. This is not because that driver has a lower power-handling than the others. It is because the driver is reproducing greater LF and low-mid output than the others and is physically working harder to do so (maximum diaphragm excursion at these power levels). It requires a lot more power to displace the air needed to generate low frequencies compared to mid/high frequencies. It also requires a heavier duty driver capable of greater diaphragm excursion to reproduce them at a given SPL. The Knowles Dumbo is not far behind the SSS driver in full bandwidth output and power-handling, and it starts to crackle just a dB or so after the SSS driver. The Dumbo has a higher self-resonance and a few dB less output below 200Hz, which accounts for this perceived (though not broadband) headroom. This is a side effect of trying to achieve broadband reproduction from a full-range driver and the reason most home and professional playback systems use 2, 3, 4 or 5-way crossed-over designs. I will say that I've never noticed any Doppler distortion (or maybe more correctly stated as intermodulation distortion) from these designs, something that is common among traditional cone full-range drivers. This is likely due to the very fast transient response of these low profile micro drivers. At any rate, since I am after the broadest frequency response and lowest distortion at moderate levels, not purely high SPLs, I still stand behind my choice of driver. This driver breakdown threshold does vary slightly from enclosure to enclosure with their varying compliances, and some diesel horn sound files are more torturous than others (i.e., some decoder horn recordings have excessive low-mid frequencies that aren't needed to sound good, but do eat up amplifier and speaker headroom). A little volume mixing within the decoder cleans everything up, particularly when the default settings have the horn too loud relative to the prime mover, and I have never felt that any of my systems cannot get loud enough (though I believe some modelers run their locomotive SPL volumes much too high).

Multi-driver Designs

While Loksound decoders get plenty loud, Soundtraxx decoders tend to be able to deliver a bit more output over the Loksound's, especially with Tsunami 2's 2W amp - its quite stout! Of course, you can run a powerful Tsunami 2 at lower (sane?) levels and be just fine. While I believe users should operate their volumes at a more "scale level" (typically much lower than default), I knew I would have to bring a dual-driver model to market if I wanted to appeal to more users.

I tried spacing the drivers differently, from tightly together to opposite ends. I tried designs with the two drivers mounted to opposing sides (top/bottom), both wired absolute polarity or one reversed, baffle-divided chambers or continuous chambers. I tried various manifold and quasi-horn type designs with the drivers in a V configuration. Basically, if there was a different way to mount two drivers to one enclosure, I tried it and manipulated the internal designs and absolute polarities of the two drivers in all ways for most instances. Some of them could have been somewhat passable in the HF. None of the options-tested produced more LF, which was what I was hoping-for. All of them gave me more SPL. Which brings up a point; when someone compares any two speakers between each other, the louder one will most always win, *even if it sounds worse*. The human ear/brain mechanism is conditioned to favour a louder result when comparing two sounds (provided that neither sound is audibly offensive).

Here is a video comparing a 12mmH x 18mmW x 52mmL enclosure with both single and dual driver configurations, *not level matched*. Obviously, the dual-driver model will show an increase of SPL.

https://youtu.be/EBGK_iKngNs

Most every low profile, multi-driver speaker sold to the model railroad community simply has pair of drivers mounted to an enclosure. Sometimes the two drivers fire into the same enclosure with a continuous chamber, sometimes each driver has its own enclosure or sealed chamber from the other.

The problem with each instance here is that combining drivers in this fashion only results in more of the single driver/enclosure frequency response at best. Negative artifacts range from slightly more-resonant (peaky) high frequencies at the very least, to a louder mid-range with *less* low frequencies and peaky high frequencies being the worse case.

Separating a given enclosure into multiple chambers will help preserve the LF, though only as much as that driver could produce as if it were on an enclosure of that size by itself. None of the drivers will have as much enclosure volume as they really want given typical HO locomotive sizes. If a 12mmH x 18mmW x 52mmL box is divided into two 26mmL chambers, the LF response will have a more limited extension and attenuate more sharply than a single driver coupled to the full 52mm length.

When multiple drivers fire into the same continuous enclosure, each driver's self resonance shifts upward due to acoustic impedance mismatch within the enclosure. You are literally overloading the enclosure's cubic volume with too much air pressure. As drivers are added, the peak resonance continues shifting upward, the low frequency response continues tapering downward and the HF response continues narrowing into a sharper peak. The result is that the low frequency response worsens, the midrange hump grows bigger and the HF response becomes more piercing.

I can hear at least someone out there saying, "But everywhere, from the home stereo to band and concert sound systems, I see speaker systems with multiple drivers in them and they sound huge. It works there! It must be the right thing to do!"

Well, lets examine what the big-boys do with their big speakers and see how it might apply to us working in a 1/87 scale world.

Coupled Arrays

A coupled speaker array places multiple, similar drivers closely together, and all frequencies that fall within a 1/2 wavelength of the center-center spacing of the drivers will couple, combining as one. This is called *mutual coupling*. All frequencies that are greater than a 1/2 wavelength of the center-center spacing will destructively interact with each other and create tremendous amounts of comb filtering (sharp cancelations of various frequencies and a highly irregular response - a very bad thing). With our 13x18 low profile speakers, we can place them so closely together that all frequencies up to around 13KHz will couple together, since 13KHz has a wavelength of 26.5mm, divided by half is a 13.25mm 1/2 wavelength and our center-center spacing is only 13mm. Frequencies above 13KHz will start to quickly degrade into horrendous comb filtering. While there may not be a whole lot of useful train sounds above 13KHz, the accompanying noise and hiss above 13KHz will happily comb filter away, smearing and ruining what would be an otherwise harmonious high frequency response, creating a noisy mask over the detailed sound.

So why did various coupled loudspeaker arrays came into use in pro audio (the originator of all of this) in the first place? This may seem unrelated to our model train speakers, but understanding this will better inform you when coming up with a design. What I am about to say is the answer to the "why?". If you do something without asking yourself "why?", then what is the point of doing it at all?

Coupled speaker arrays came into use in the 1960's for these primary reasons:

Greater need of SPL output. If one speaker makes 100dB, two will make 106dB, three 110dB, four 112dB and so on, following 20log10 summation. Do you need to produce sound at a louder SPL? Adding more speakers is one way to do this, though if implemented improperly, more speakers will wreck the quality of sound and may actually attenuate the range you're trying to boost! This is one *why* more speakers were added; the need for higher SPL output.

Greater pattern control of the sound directivity. Form an audio standpoint, a single speaker is referred to as a point source, though scientifically, a point source is omni-directional of equal amplitude at all frequencies. A single subwoofer is a fair representation of a point source in our real world audio applications. As a speaker's frequency response goes down in frequency, the waves become progressively isotropic (omni-directional) in nature and propagate in a spherical wave shape. Speakers placed side-by-side are parallel arrays. When stacked high or wide and spaced within 1/2 wavelength of each other, they will couple and their directivity pattern narrows perpendicular to their inline axis (either vertically or horizontally, depending on the orientation). When you go to a concert and see subwoofers lined up across the stage, this is a parallel array. They will mutually couple together, frequency dependent upon their spacing, and will have a narrower horizontal throw pattern and a wider vertical throw pattern, verses what a single subwoofer would exhibit, which would be more or less omni-directional. Sometimes you will find subwoofers stacked (or flown) vertically, so that they have wider horizontal dispersion and narrow in the vertical field. Lining up enough of these speakers creates roughly a line source, propagating a more cylindrical wavefront, and this array will exhibit a stationary wide horizontal dispersion and an increasingly narrow vertical dispersion as the array grows in length. This is **the why** column loudspeakers became so popular in the 60's; one could stack multiple full-range 8", 10" or 12" drivers vertically, obtain the greater SPL output required, all the while creating a wide horizontal dispersion to the audience and simultaneously narrowing the vertical throw, keeping the sound from bouncing off the ceiling/floor. They were not developed to increase the low frequency output or broaden the response to a more pleasing sound. In fact, they did quite the opposite! They were/are effective for the speech range and thats about it. Some of them did/do add dedicated highfrequency drivers/horns to extend the HF upward. Modern systems utilize smaller drivers to increase the HF coupling while adding dedicated subwoofers to extend the LF. Large-format line-arrays utilize multiple bandpassed driver sections (3 to 5 ways) to reproduce a broad-band spectrum that hopefully couples in all bandpasses.

Faster transient response. Smaller drivers, *only if all things are equal*, will have a faster transient response due to lighter diaphragm mass. In the early years of pro-audio and home audiophiles, transducer technology and advancement was painfully lacking. By using more smaller drivers, as opposed to fewer larger drivers, a similar amount of air pressure at a given SPL can be displaced while gaining better transient response. This is *why* the ubiquitous 8x10" bass guitar amp cabinet came into use. Again, *all things being equal*, a 10" driver will have a "punchier" sound with more clarity and definition (transient response, HF response) than a 15" driver could reproduce at the time. Add a few 10" drivers together and you can achieve the same LF potential and output that a single 15" driver can produce, but with better definition and transient response. Home audiophiles also experimented with small driver coupled arrays for the same reason. I emphasize "*all things being equal*" because there are heavy, slow 10" drivers and light, fast 15" drivers; all things are rarely equal. Transducer technology, while still using the same principle of design for over a hundred years, has vastly improved in performance over the past 40 years.

Thus, speakers are added to 1) increase SPL output, 2) control directivity and 3) improve transient response. If there were a perfect driver (or even a complete speaker) that could produce the desired frequency range across the required coverage area at the desired SPL needed, I assure you that speaker arrays would never have been invented or would no longer exist! Speakers are arrayed out of necessity; not because it makes the sound better!

So what does all this mean for our locomotive sound applications?

On the next page is a graph comparing the response of the previously discussed single-driver mounted to the 12x18x52 enclosure, the same enclosure type mounted with two drivers coupled to their own chambers and the same enclosure with both drivers coupled to a continuous chamber. This graph and the following videos reflect *output levels being matched*.



Note how the single-driver system exhibits both more power in the low frequencies and a lower resonant peak. The ripple around 3KHz is the result of coupling a driver to a large enclosure without any internal enclosure design. The single-driver example also has a more rounded presence peak placed a little higher.

By comparison, both dual-driver systems show less low frequency output, a pronounced HF resonant peak that is lower in frequency and sharper in width and we begin to see a lot of response ripple above 12KHz, a result of the drivers no longer coupling and comb filtering setting in.

Here is a *level matched* video of the previously shown unmatched video, comparing the same single-driver and dual-driver systems.

https://youtu.be/9c_ubCdKz4k

Obviously, now that we're hearing the two systems level matched, its clear to hear the single-driver system produces more low frequency power and has a smoother sound overall.

So then, if two speakers make it worse, four speakers must make it really bad! Lets compare the same, single-driver system to a four-driver system on the next page and see if we can really muck it up!



Note again how the single-driver system exhibits both more power in the low frequencies, a lower resonant peak and a more rounded presence peak.

By comparison, both four-driver systems show even less low frequency output and a higher low resonant peak that has shifted up higher than the dual-driver model. Likewise, an even sharper HF resonant peak at a higher amplitude and vastly more response ripple above 12KHz than the dual driver example displayed.

See the progression of degradation in sound from single to two-coupled to four-coupled?

Here is a *level matched* video comparing the same single-driver system with the four-driver systems.

https://youtu.be/2CEdLbj6tVM

The third common addition method is multiple, separate, individual enclosures lined up. Say you have 13x18 drivers all mounted to separate enclosures that measure 12mmH x 26mmW x 15mmL. Again, you'll make more SPL, but the LF response is only going to be as good as what a single one of those speakers could produce and the HF response will continue narrowing, becoming more "peaky", as in all of these situations. Even so, with the specific enclosure size stated here (which is my AHGM-F701 system), the drivers are now spaced at a distance of 15mm center-center and thus will only couple from about 11.5KHz down, with everything above 11.5KHz suffering severe comb filtering.

On the next page is a graph comparing the response of a single F701 and a coupled array of four F701s. This graph and the following videos reflect *output levels being matched*.



The LF boost of the single system may have been a measurement anomaly, since in theory at least, the LF response between the two should be quite similar. I do seem to notice just a touch more LF extension with the single system's sound. Note the overall smooth response with a more rounded presence peak and roll-off.

By comparison, the four-coupled system shows a less smooth response with some addition around 5KHz and a much sharper, resonant presence peak. We also observe an uneven response and ripples starting just above 10KHz, a result of the drivers no longer coupling and comb filtering setting in.

Here is a *level matched* video comparing the single F701 system with the four-coupled F701 array.

https://youtu.be/7pM0xEQ6jWg

You just heard what a single vs. four-coupled F701 array sounds like. Now lets go back and hear the singledriver 12x18x52 system compared to the four-coupled F701 array:

https://youtu.be/n5mvrPd8m_U

The single-drive system occupies a space of 12x18x52mm and has much more low-frequency output and a smoother, more detailed sound than the four-coupled F701 array that occupies 12x26x60mm of space!

Coupled Arrays: Good for Loud Sound, Bad for Good Sound

So now we know that adding drivers or speakers spaced center-center within a 1/2 wavelength of a given frequency allows them to couple and be louder. That's good, right? This is our friend named power addition. Our friend here, being a good hearted mate, does not discriminate between any frequencies that fall within the 1/2 wavelength coupling range. It is all frequencies falling within the 1/2 wavelength spacing that gain the boost from mutual coupling.

If your single speaker (again, a driver+box/chamber) is operating at a range of 300Hz-15KHz and you add a second, third, fourth, etc., the single speaker's lower range of 300Hz up to about 13KHz (if the drivers are spaced 13mm apart) will all benefit from the mutual coupling, but at a rate that is similar to the single driver's response. You are adding power (increase) to all of those frequencies and creating higher SPL output; *you are not shifting the array's frequency response downward and gaining "free" low frequencies, quite the opposite in fact!* Furthermore, as more drivers or speakers are added to the array, the high frequency peak will narrow and become more resonant (piercing) while all high frequencies above the coupling range will suffer devastating comb filtering.

If we had the room within our HO locomotives to deploy multiple, ideally sized enclosures, then a coupled array could work quite effectively for both broadband response and output. But given the space constraints we have to work within, it is better to have one optimally designed system than multiple compromised systems arrayed together. The answer to more LF extension, smoother frequency response and a detailed sound is more enclosure; not more drivers.

In summary, it is impossible using these techniques to obtain greater low frequency output or a better sound by simply adding more full-range drivers or speakers. All of these techniques induce varying degrees of artifacts to the overall system response. Overcoming the response limitations of these designs by wantonly boosting EQ is a terrible and tragic solution to a problem that was needlessly created. The amount of low frequency EQ boosting required will not only reduce headroom, it will increase distortion, putting undue stress on the drivers as they attempt to reproduce frequencies that are being acoustically canceled out. In short, if all you need is louder, by all means, throw as many speakers as you can fit into the locomotive. If you want the sound to be bigger (a broader frequency response) and more detailed (smooth response, fast transients), lining up speakers in a row is not the answer.

So how can one increase power and output without sacrificing quality?

Scale Sound System's Coeval Series dual-driver designs utilize two similar drivers in a true, diaphragmdiaphragm, sealed-isobaric arrangement. The two drivers are wired reverse absolute polarity so that they move and work as one, completely phase coherent throughout their range. In theory, a design such as this suggests a 3dB increase in the LF power and my own measurements have reflected this. This is as close to "free bass" as you can get in such a small design! Driver damping increases, so transients, detail and HF response are maintained or improved. In fact, the mid and high frequency response stays nearly identical to that of a single driver, within a dB or so throughout the entire range. The HF presence peak is also slightly more-rounded in a pleasing way. Twice the power handling, 3dB of extra LF output and the same, smooth, phase coherent sound of a single drive speaker system is the result of thoughtful engineering.

Shown is a comparative graph for an Athearn Genesis GP40-2. The green trace reflects the stock speaker that comes in the locomotive. It exhibits strong sensitivity between 1.8KHz and 7.4KHz, rapidly rolling off below this band range. The average amplitude within this range is about -3dB. Note the amplitude at 200Hz is -35dB. This is a midrange to low frequency level difference of 32dB!

In contrast, the Scale Sound Systems AHGS-3850-087 Rectify and AHGS-3850-CO8 Coeval models show a broad hump centered around 470Hz with a smooth, subdued midrange response averaging -12dB and a presence boost at 7.7KHz. At 200Hz, the Rectify model is -18dB while the Coeval model is -15dB; a midrange to low frequency difference of only 3dB or 5dB, respectively! Note that both SSS models remain linear to 100Hz, with the Coeval model maintaining it's 3dB additional LF power!

At first listen, the observer may conclude that the stock speaker is louder. Between the band-range of 1.8KHz and 7.4KHz, the stock speaker indeed is. The human ear is most sensitive in the 2KHz - 5KHz band-range and more easily hears these frequencies. This was well documented by Harvey Fletcher and Wilden A. Munson in their 1933 paper entitled "Loudness, its definition, measurement and calculation" in the Journal of the Acoustical Society of America.

The Scale Sound Systems speakers balance this imbalance of our hearing, boosting the low frequencies we are less sensitive to, but desire to hear, while gently subduing the midrange band our ears are more easily able to perceive. When taken from a broad-band perspective, it is easy see (and hear) that the Scale Sound Systems speakers are considerably louder than the stock model.



Page 16: Concepts and Considerations in Speaker System Design, Scale Sound Systems 2018

Here are *level matched* videos, comparing the stock Athearn speaker with the Scale Sound Systems Rectify and Coeval Series speakers:

Tsunami 2: https://youtu.be/IUNV_JS-0b0

Loksound: https://youtu.be/go3Hbl6MRv4

Closing thoughts

The purpose of this paper is two-fold; to shamelessly promote my own speaker systems by demonstrating the amount of time and skill (learning + knowledge + experience) that was spent in designing the highest performing speakers that I can for small scale model trains; and to inform those who wish to embark on their own speaker designs. *My specific designs and methods are my own and will not be disclosed*. Hopefully you found this paper both enlightening, enjoyable and helpful, wether you choose a Scale Sound Systems product or not.

As one final thought; I want to make it clear that I am in no way shaming other modelers or manufacturers! Many modelers and manufacturers have made great strides in improving the quality of DCC locomotive sound. I will happily applaud anyone who takes the time to experiment and work towards better sound. To that end, my products will not appeal to everyone and I make no claim or guarantee that my products will satisfy everyone. Scale Sound Systems was born out of my personal desire to achieve something better and through the encouragement of friends and clients, I have brought them to the general public for their consideration.

Thank you for taking the time to consider my thoughts.

jt burke

About the Author

jt burke is a professional audio engineer with 25 years of experience in large-scale live sound reinforcement, working as a FOH/MON mixer and system design/tech. He's toured the world with many A-list artists. He also occasionally works as a design/build sound installation contractor and consultant. His greatest passion is recording studio engineering/mixing and he owns/operates Fathom Fidelity, the private studio he's worked from since 1995. He's had numerous Top40 radio singles on various charts and Billboard 200 albums to his credit.

Acknowledgements

I must thank those who have gone to great lengths in supporting the work I do with Scale Sound Systems. Chris Palomarez of Athearn was an early customer and has been a huge advocate of "spreading the gospel" of my little endeavor. George Bogatiuk of Soundtraxx, who's provided helpful feedback. Paul Gillette of the Model Railroad Hobbyist Podcast, who's enthusiasm has fueled new products. Jim Wells of Fantasonics Engineering, who's always gracious with advice and support. To my numerous clients who persuaded me to release my products to the public in the first place. Thank you all!

Lastly, I would be remiss if I did not acknowledge Prof Klyzlr for his scrupulous proof reading and editing of this work. I would not be the least surprised if he didn't contribute guidance on this very sentence. This proves that it pays to pay attention in English class as well as reading audio and train magazines!

All content is Copyright 2018, jt burke/Scale Sound Systems and may not be shared, reproduced, modified or published without prior written consent.

Page 17: Concepts and Considerations in Speaker System Design, Scale Sound Systems 2018