

Practical Comparison of Transmission Line (and Transmission Line Like Enclosures) vs. Bass Reflex

Or

“A Tale of Five Speakers”

By

Scott Hinson



Introduction

A few weeks ago, I published two writeups on labyrinth style ports and transmission line style speakers. To say that those two papers generated, ahem, significant discussion would be the understatement of the decade, possibly longer. What started as an attempt to provide some real-world examples of how to measure, evaluate and make decisions on loudspeaker design took off.

Inevitably some of the comments/questions/messages I received asked about design options that I hadn't tested.

"Well, what would a transmission line stuffed with kittens sound like?"

Wasn't actually a message I got, but I did get so many requests that I decided to add on to what was already a fairly involved set of measurements and prototype loudspeaker cabinets. Unfortunately, there are so many possible options that it's impossible to construct and test all of them. Since I am not independently wealthy nor a man of leisure, I had to limit what I built and tested to the most common constructions seen in the DIY world.

So, what **is** this paper? Over the years I've read a bunch of things about transmission lines, mass-loaded transmission lines and other types of speakers. Years ago, my first real speaker was the Sony SS-TL1, which 14-year-old Scott thought sounded amazing, and today year-old Scott thought it would be cool to make something with those dimensions and operating principles. The first prototype cabinet started this investigation....and this investigation has slowed down the completion of that speaker. Oh well. What quickly remembered after making that prototype is that transmission line style speakers are a challenge to design. And many of the things that I have seen online about transmission lines aren't really justified by the measurements of actual speakers. So, I thought I would do a practical, real world, measurement heavy comparison of transmission lines (of various flavors) compared with bass reflex speakers. My hope here is that these measurements form a solid grounding for a discussion of the designs, dispelling some of the errors and myths we have all seen. I'm also hoping that when I point out differences in behavior between bass reflex vs. transmission line systems it's useful for those developing models, some of this stuff isn't common knowledge and it might be good to stimulate a few ideas.

What **isn't** this paper? This is not an attempt to validate the modeling tools used to design these programs. Yes I used Hornresp and other tools to model these lines....but you won't see those models compared to the end results, it's just not the purpose of the paper. Not only that, but I've talked at length about the limitations of Hornresp in the Neman Horn subwoofer paper, the dual 18" bass reflex PA subwoofer paper and the modeling software comparison paper. It also isn't an attempt to tell people not to build TL based speakers. (Spoiler, I won't



be spending a lot of time on them after the SS-TL1 project, but that's my decision. I'll tell you why in the paper...but you can always decide to build a TL if you want...I can't stop you.)

At the end of the testing/building process for this speaker I'd consumed 2 sheets of MDF, made well over 400 measurements and spent a good 30 hours looking at the resulting data and completing this writeup.

Definitions and Historical Context

Before we get to the actual measurements we have to go over some definitions, so we have the same understanding of what we are looking for at each step.

First things first, what is a transmission line? Way back in the end of the last millennia when I was in engineering school, we were taught the following definition:

A transmission line is a structure designed to conduct EM waves where the line is long enough the wave nature of transmission must be taken into consideration.

Huh? Without going into great detail, at high frequencies the signal can travel down the structure (coaxial cable, twisted pair etc) without significant reflections or attenuation due to losses from the cable radiating the electromagnetic energy into the environment or impedance discontinuities. The audiophile world loves to talk about this and speaker cables but most of it is...silly. The frequencies are too low and there's no real matching happening.

So, can you use this definition for speakers? You can try, but it won't work particularly well. In Bailey's original work¹ it certainly seemed like he was trying. It wasn't a particularly convincing attempt. From the article:

"It is now apparent that it is the sound wave produced at the rear of the cone that have to be absorbed if delayed output and resonances are to be avoided."

He then goes on to describe a speaker constructed in what we would call a three-segment transmission line, where the terminus (open end) could be left open or closed through a rotating door/flap type arrangement. One very important thing to note is, if this was a structure that absorbed the energy from the rear of the cone, it wouldn't matter if the flap was open or closed, both would have the same response.

But they don't...and Bailey freely admits it.

"Opening the port had two effects. First, the bass response was improved to become approximately flat and secondly the cone excursion was greatly reduced between 30 and 50c/s."

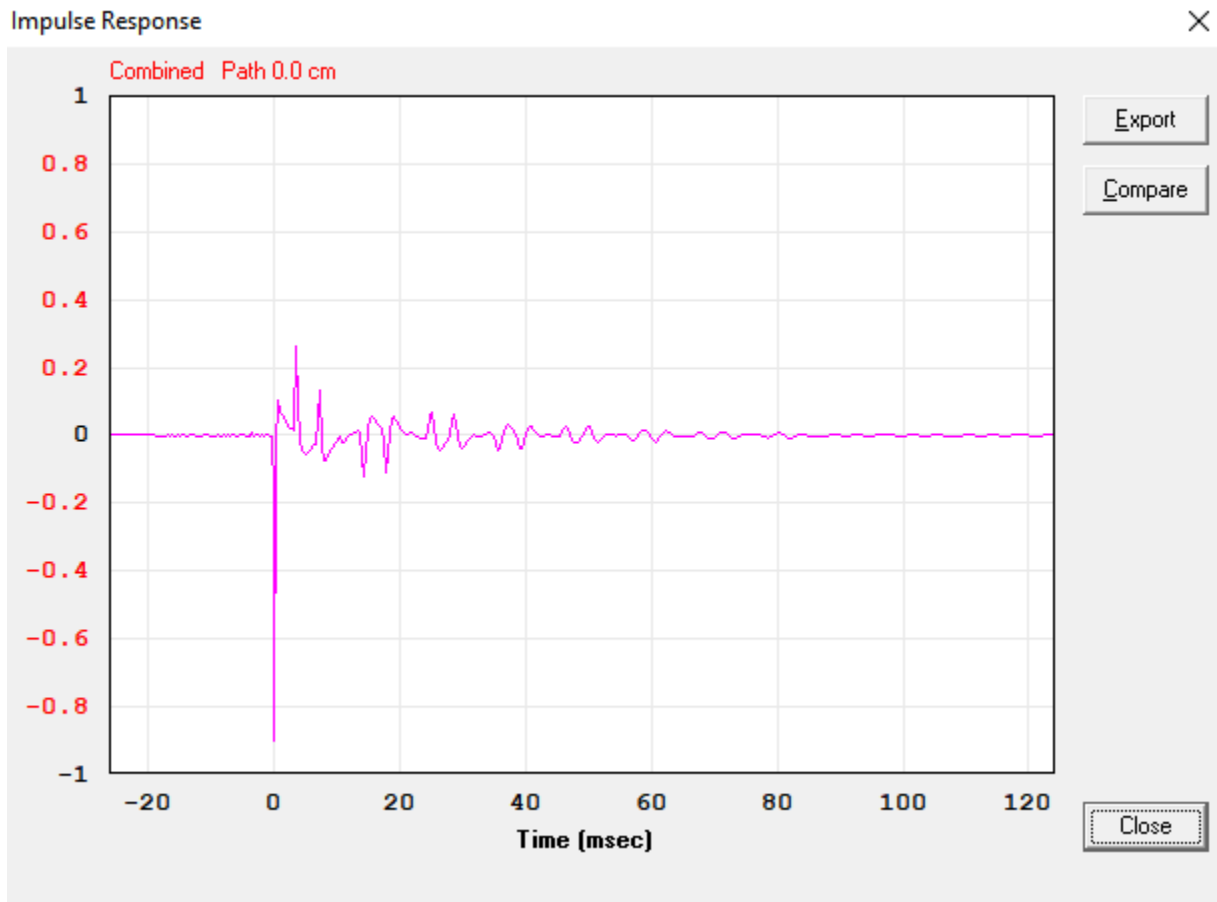
¹ A Non-resonant Loudspeaker Enclosure Design, Wireless World, October 1965, A. R. Bailey



Now here's where it gets pretty iffy.

"The bass improvement was due to the line length being such that the delayed bass wave from the line was in phase with that radiated by the front of the cone. Also as the bass frequencies were radiated from two spaced sources, the diffraction effects would be reduced."

In this case in phase doesn't mean at the same time....you can have a sound that is delayed by several cycles and under steady state conditions they can be in phase and sum. In this case the terminus output won't be delayed by several cycles, the pipe/line isn't long enough, but it is delayed. You can see that in the simulation from Hornresp. I do suspect that many of the purported transmission line phase benefits are because folks are misinterpreting what Bailey wrote here....and I am wondering if Bailey misinterpreted his measurements. What does the impulse of a transmission line like Bailey's look like?



You have the initial impulse of the driver, followed about 5ms later with the terminus output, and then reflections at multiples of that later yet. This shows that the structure Bailey described and the electricity transmission line are very much not the same. All those reflections wouldn't be happening if there was a good acoustical impedance match. There's a few other



dubious things in that original article...including a purported method of testing the cabinet resonance with a spark source, but next we'll move to the 00's for the next major step in TL design and understanding. Very close in time to each other Martin J. King and George Augspurger published models of transmission lines. Augspurger's work came out in an AES paper in 2000, King's work came out via the Quarter-wave.com website in 2002. Again, this paper isn't designed to be a deep critique of either approach, but King's modelling effort is superior to Augspurger's, generally yielding better results. However, there are a few concepts to be drawn from both, without diving headfirst into a lot of math that would hurt our collective brains.

Augspurger

Augspurger points out that modelling transmission lines without assuming damping fiber motion has been shown to give good results, with the models being simpler due to the assumption that the fiber isn't moving. He doesn't actually address whether he thought the fibers were moving or not...just that the model doesn't need to know that. (King later concluded the fiber isn't moving through derivation of the phase rotation of the delayed line output at the terminus). I'm not sure what the impact of my next few sentences will be, because I haven't dug into the models enough to predict what should/could change...but here we go. I put both poly-fil and acousta-stuff into the straight TL I built for this paper and observed motion in both types fibers at relatively low volumes. Unfortunately for all of my efforts to get video of this motion, the subject is difficult enough I couldn't get a good demonstration. I have speaker skilz, not video skilz yo.

He also points out that the different damping materials do have different results in the line....and those differences change with packing density. My takeaway for this is that if you're going to build a TL, and you're looking for unit to unit consistency the line stuffing material has to be well specified, and substitutions should be discouraged. In Augspurger's own words: "In transmission-line systems, if the pipe output is appreciable, then these small differences may be audible."

Augspurger also points out that some people have reported unrealistic results from very high-density stuffing in short transmission lines. I have seen many unrealistic claims of bass performance over the years as well, usually involving smaller lines, smaller drivers and a lack of actual measurements. If someone is claiming that a 5" woofer in a t-line "hits as hard as a 10"...just walk away. Physics is undefeated and the hyperbole isn't warranted.

He also covers some different physical formats, tapered lines, vented boxes with long aspect ratios, transmission lines with some amount of air chamber prior to the line etc. No guidance is given if any of them are objectively superior, most likely because, again physics being the law and not just a good idea, none of them are inherently superior.



Lastly he talks about the directivity of Transmission Line speakers, referencing a 1975 thesis by G. Letts that I couldn't find. I would love to delve into this more, so if someone has this paper, I'd love to see it. I suspect I understand what he's talking about given the typical distances between terminus and driver....but I'd like to see what was written before commenting.

King

Martin J. King released a series of documents and a Mathcad model in 2002. At the time it was one of the more complete tools you could get for simulating transmission line style speakers on the internet. This paper isn't designed to dive into the model itself, but there are a couple of points that are worthy of addressing before moving on to the speakers I built and measured...and the conclusions I've reached from them.

Instead of concentrating on that original series of 7 papers + references² I'm going to look at two more modern publications. The first is "The Two Year Transmission Line Speaker Design"³. In this document King describes the design process for bass reflex and transmission line designs, concluding:

"For the same floor standing enclosure, an equivalent transmission line is a more challenging sketching exercise"

Here we totally agree. King points out that the folding of the line, accounting for changing cross sectional areas while keeping the outside dimensions usable is difficult. The only thing more difficult is folding big bass horns. What King seems to leave out of this paper is that the transmission line design bass response is also much more dependent on stuffing than the bass reflex design. That's problematic since it's beyond the scope of many DIYers to build the numerous prototypes and do all of the measurements needed to hit the bass alignment desired, speaker size required, and pipe resonance mitigation needed for good sound.

The second piece is a presentation dated 11/2/2023 entitled: "Using Modal Analysis to Understand Transmission Line Speaker Enclosure Response Part 1- The Basics."⁴

This one has a section on equivalent bass reflex and transmission line speaker systems.

² http://www.quarter-wave.com/TLs/TL_Theory.html

³ http://www.quarter-wave.com/Project13/Satori_TL_Design_Documentation.pdf

⁴ http://www.quarter-wave.com/Project13/Part_1_The_Basics.pdf



Definition of Equivalent BR and TL Speaker Systems

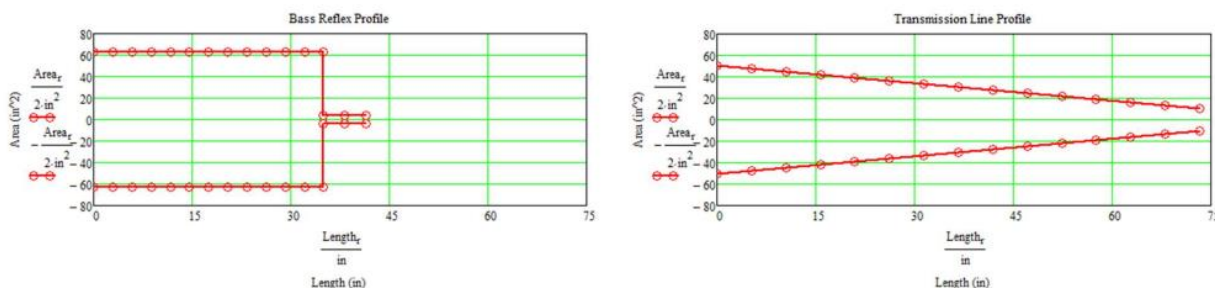
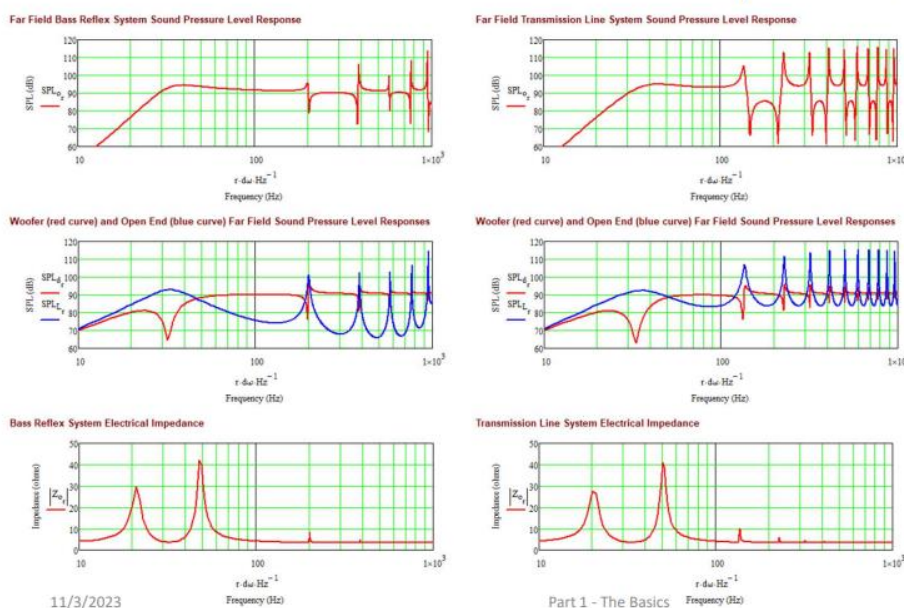


Figure 1 MJK Equivalent BR and TL Speaker Systems, Source: http://www.quarter-wave.com/Project13/Part_1_The_Basics.pdf, retrieved 12-1-2023.

King then goes on to show his model results for both systems.

Calculated SPL and Electrical Impedance Responses



System resonances occur when the driver's cone and/or the open-end velocities peak.

Electrical impedance peaks are driven by the driver's cone velocity.

There are multiple resonances in both the BR (left) and TL (right) plots. Most freeware programs do not show the higher frequency resonances that occur in BR enclosures. This is a limitation of the lumped parameter modeling.

Figure 2: BR and TL Responses, Source http://www.quarter-wave.com/Project13/Part_1_The_Basics.pdf, retrieved 12-1-2023

Note in the side text that King points out that existing lumped element models such as Basta!, SoundEasy and others don't account for the enclosure resonances like his model does. This is true, they typically don't. Some more advanced versions will include the pipe organ resonances



of the port, but that's not always a guarantee. I'm not sure I'm that bothered by it though...since in practice in a bass reflex box, those resonance modes aren't nearly as bad in the nodal model indicates. Hornresp has the ability to adjust losses for the vented enclosure models, you can remove all of them and get an answer similar to the King model, and then put them back in to get something closer to what the lumped element simulators (Basta!, VituixCAD, WinISD) provide. It doesn't have that function for transmission lines or horns...so in practice when you build those enclosures you don't see peaky behaviour nearly as strong as the model predicts. The major reason is that enclosure losses are higher than people realize, and those sharp resonances can't develop. The good news is that the frequency response is generally significantly better than the peaky response this type of model gives. The caution I would provide here is that if you're depending on a resonance-based system for sensitivity as part of your bass alignment, you might be sorely disappointed in output capability once those higher order resonances are damped to the point of being inaudible.

The second thing I noticed is...these two "equivalent" systems do not have equivalent output.

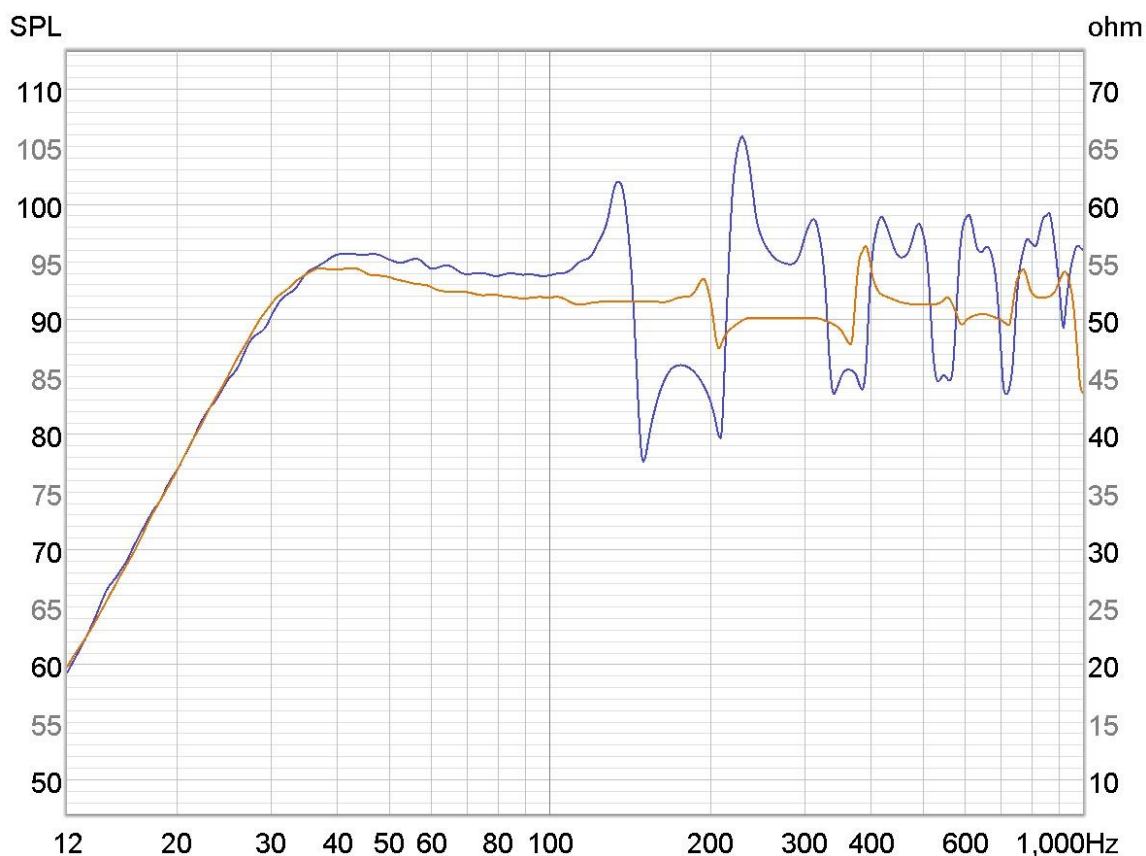
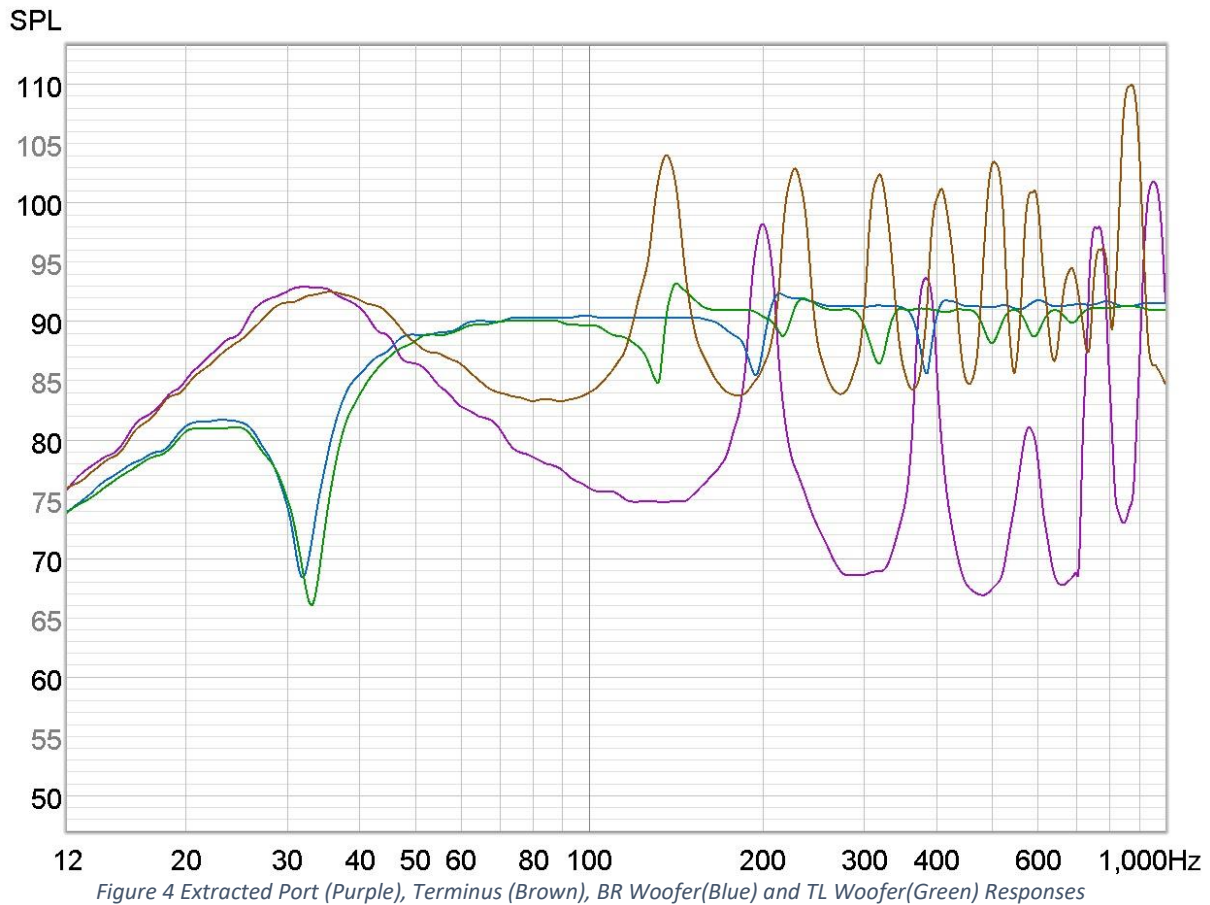


Figure 3 BR (Orange) vs. TL (Blue) from MJK Presentation

I extracted both modelled system SPL from the paper using the VituixCAD spl trace function. The TL system has higher sensitivity from just above the tuning frequency...but why? If you



study the curves the terminus output of TL has a lower Q, meaning that extra output is coming from the terminus.



In the case of these two enclosure types, I would say they are not equivalent. They can be modelled with the same underlying physics, but the predicted output is obviously not the same. I wouldn't call them equivalent.

The extra sensitivity comes from the terminus output, and in this case since the enclosures are largely undamped you probably wouldn't get that extra terminus output in practice. You'll end up putting a fair bit of damping material to tame those resonances at higher frequency and that will impact the low frequency alignment. I would posit that damping that line has a greater impact on the low frequency alignment than a BR box and the differences are exclusively losses in sensitivity...making it less desirable. I don't want to have to give up free bass.

So....now that I've said all that...and we are 9 pages into this thing....what did I do to add to the conversation?

I built 5 speakers, over the course of 4 weeks and measured the snot out of them. That way



we can ground some of this discussion with real measurements on real speakers since comparing the designs in simulation depends on the simulation considering all of the other factors that might be present and the simulation actually being correct.

The Five Speakers

Here's what I built and tested...

1. Single segment transmission line, driver offset or not. (TL-1)
2. Classic two segment folded line with offset driver (SS-TL2)
3. Two segment, folded tapered MLTL type line with offset driver (MLTL)
4. Bass Reflex with 3" diameter 150mm long straight walled port (BR-Straight)
5. Bass Reflex with ~3" diameter 150mm long port, roughly modelled on the profiles in the 2019 paper by Brezzola. (BR-Swoopy)

All speakers were built using $\frac{3}{4}$ " MDF. The idea for each design was to isolate the difference between them to a single variable, or two variables at most. For instance....comparing the two segment folded line (SS-TL2) to the bass reflex (BR-Straight) box I aimed to have as similar as possible tuning frequency, matching alignments as close as possible. Comparing the TL-1 to the SS-TL2, I aimed to have the cross-sectional area (CSA) and line lengths the same. In each case I was interested in isolating a few areas of performance for comparison.

Anyone who has done a lot of comparisons between different design choices of speakers recognizes that it's not possible to isolate one variable easily, many times you have more than one thing changing on you. I worked quite hard to isolate each variable I was studying, and the results here are about as good as you're going to get. It would be a herculean effort to do substantially better.

Straight Transmission Line

The straight transmission line was built to have the same cross-sectional area (232cm^2) and physical length as the 2-segment folded line. I built the TL-1 to have the option of locating the driver at the very end of the line, or roughly $\frac{1}{3}$ the way down the line where the driver is mounted in the SS-TL2.

In order to make the line easier to construct and measure I did have to build it in two sections, since it's just over 5.5 feet long. The two sections are sealed to each other using multiple clamps and foam to provide an airtight, rigid connection. The resulting system was strong enough that I can lift the entire line without the box flexing.

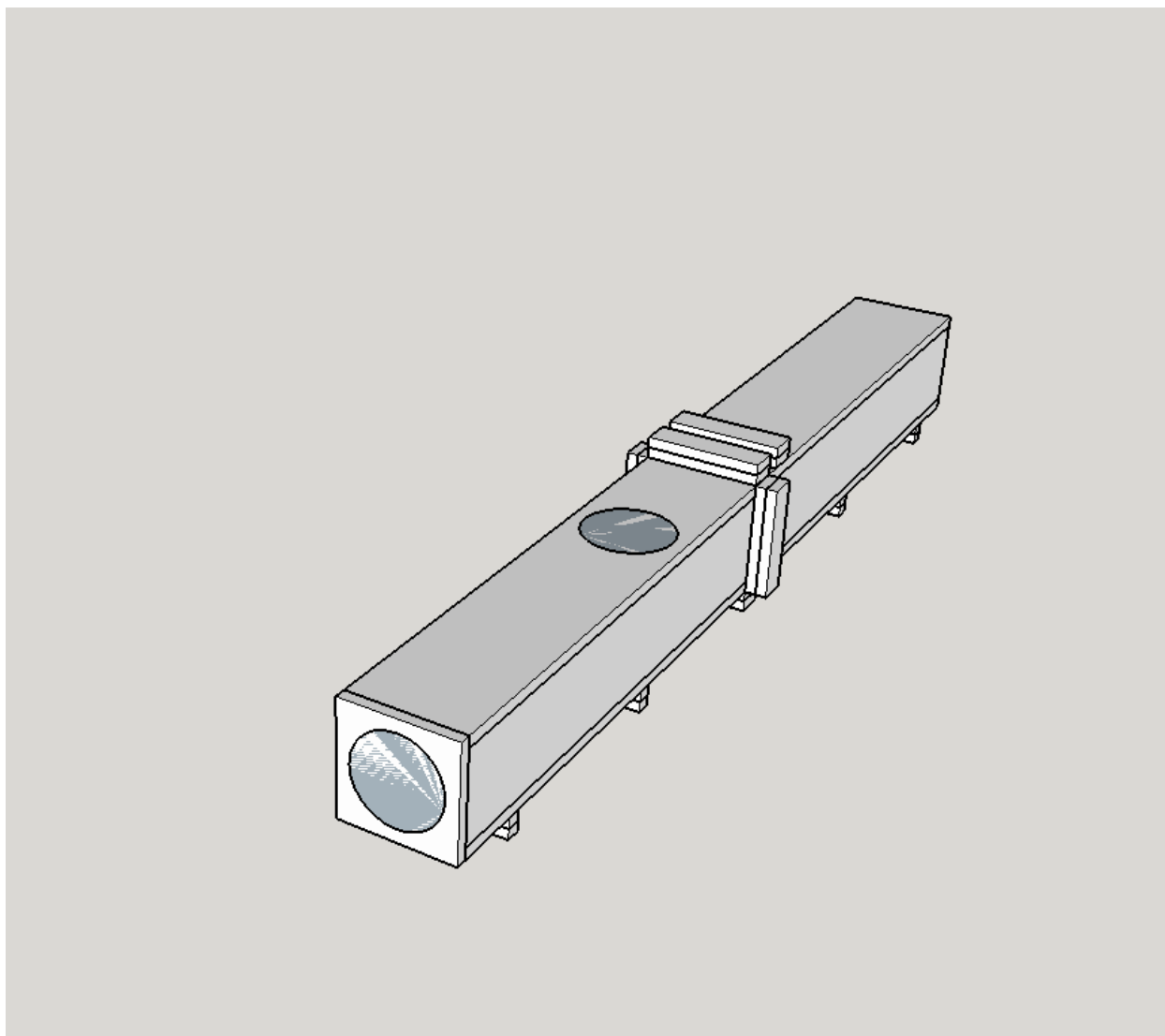


Figure 5 Sketchup Model of TL-1, note two potential driver mounting locations.

I also made a plug for the driver holes, that consisted of an MDF round .5mm smaller in diameter than the driver hole that I could screw to the enclosure providing a smooth surface internally, eliminating potential for turbulence due to a discontinuity.

Two Segment Line.

This speaker was designed to have the same rough form factor of the Sony SS-TL1 that I have emotional attachment to. Same cross-sectional area as the TL1, but slightly different aspect ratios. The line length was determined using the centreline method....and is physically the same as the straight line.



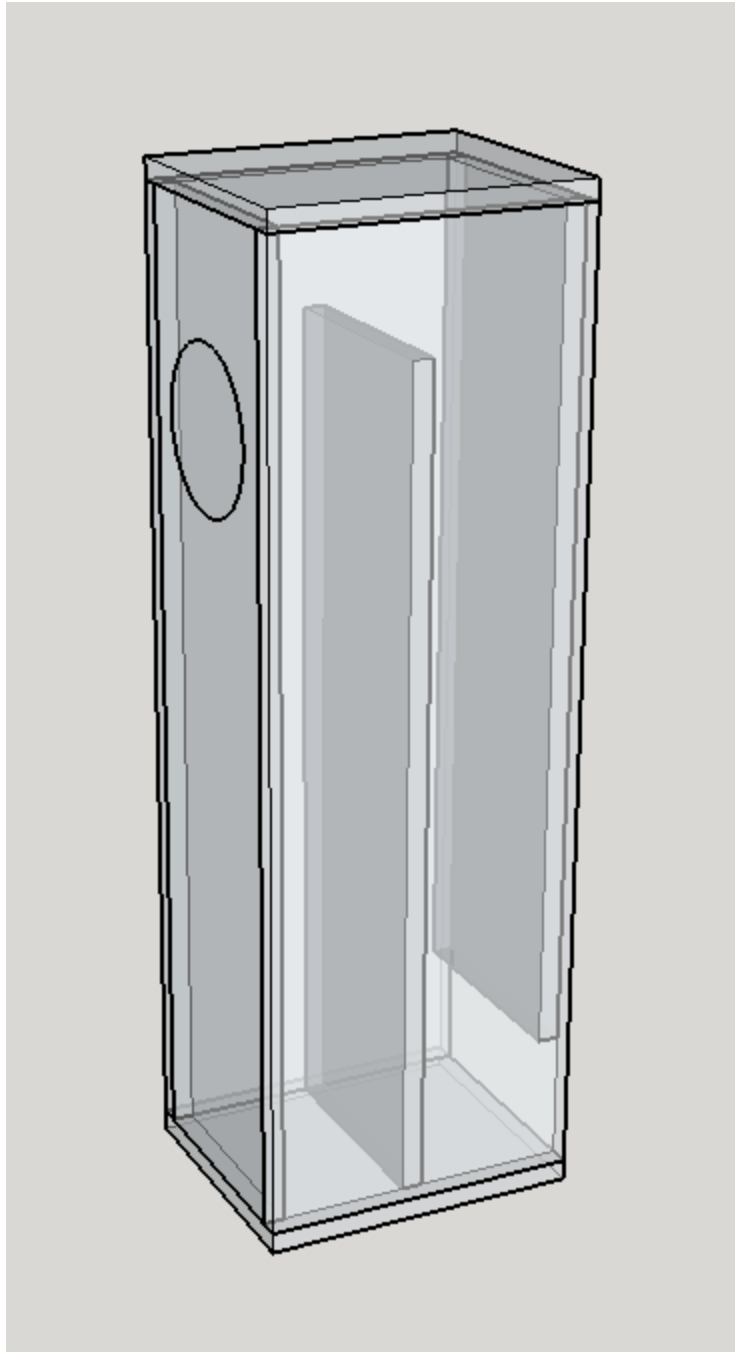


Figure 6 Sketchup Model of SS-TL2

Mass Loaded Transmission Line

Both of the previous designs have a larger internal net volume than the driver in question (Hi-Vi L6-8R) was happy with for bass reflex enclosures. Since the assertion was that you can create a TL based design with the same volume, I went for it. The bass reflex alignment was pretty happy at 30L, while the straight TL and 2 segment TL both enclose 42L of internal volume.

The design I came up with for the 30L MLTL was as follows:

Parameter	Value
Ang	2.0 x Pi
Eg	2.83
Rg	0.00
Fta	-2.76
S1	329.00
S2	249.39
S3	0.00
S4	0.00
S5	0.00
Par	49.10
Par	98.30
L34	0.00
L45	0.00
F12	0.00
F23	0.00
F34	0.00
F45	0.00
Sd	127.20
Bl	7.56
Cms	5.85E-04
Rms	1.11
Mmd	13.49
Le	0.30
Re	7.16
OD	1
Vrc	0.00
Lrc	0.00
Fr	0.00
Tal	0.00
Vtc	0.00
Atc	0.00

Comment: MLTL HI VI I6 phase plug 8 Ohm

Previous Next Edit Add Delete Record 1119 of 1123 Calculate

Figure 7 ~30L MLTL

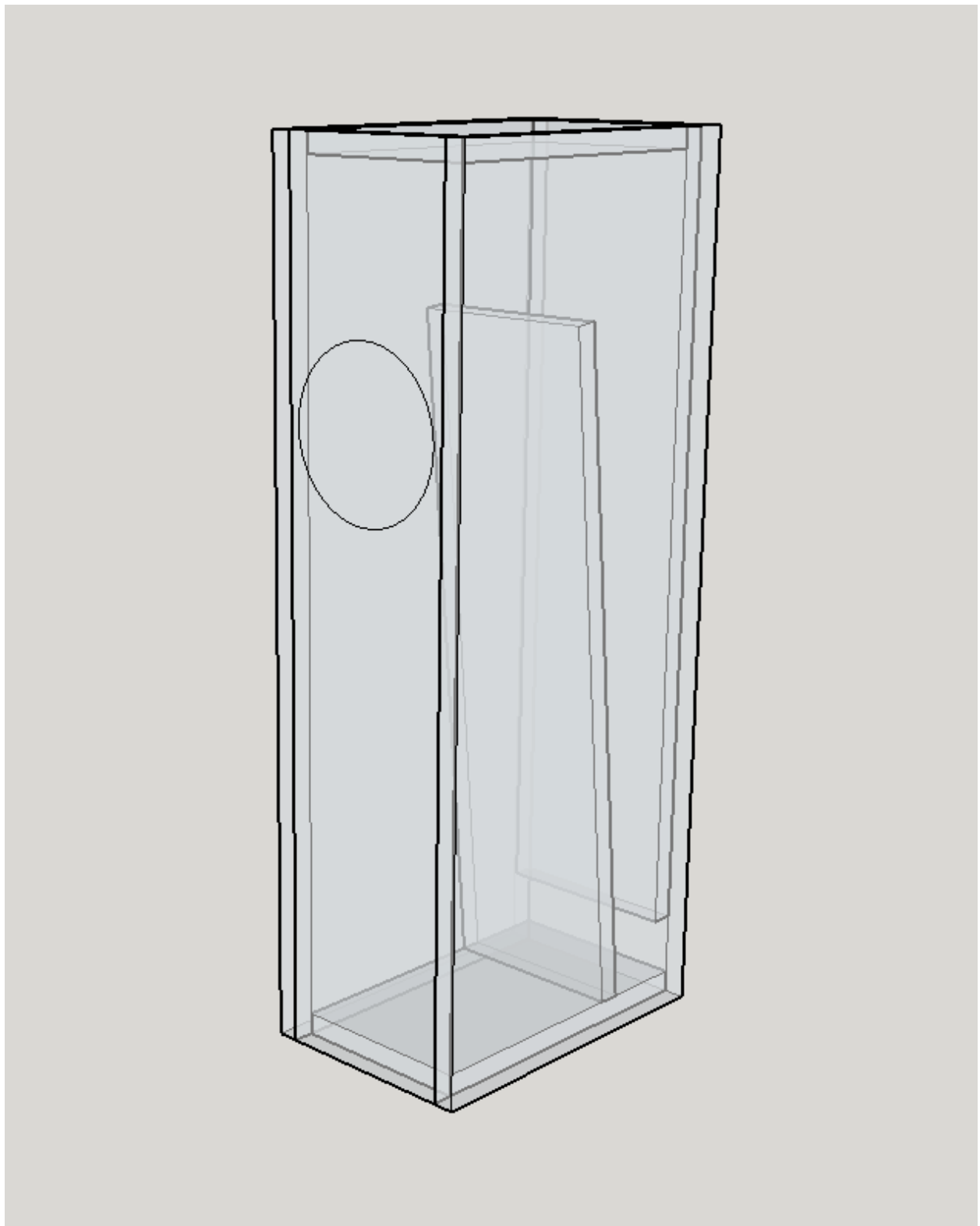


Figure 8 30L MLTL



A single divider was used, at an angle of 5.6 degrees. The total line length for this was about 20cm shorter than the straight lines, but the tuning frequency of mid 40's was maintained.

Bass Reflex

I built two bass reflex boxes...both 30L. I actually only made one box but made the port swappable by having a swappable panel about 6" square, held in place by 8 ¼-20 bolts. I used two ports, one 75mm x 150mm and the other...with a very particular shape. The box itself had the same dimensions as the MLTL, and the same driver location on the front baffle.

But the port. The port is the thing. A 2019 paper, "Loudspeaker Port Design for Optimal Performance and Listening Experience" outlines a port shape that has significantly higher performance than a straight port⁵. (I know, my previous port paper said just port it....I did it before this Harman sponsored paper came out. My DIYRM port writeup came out in March of 2019, the Harman paper was published in October of 2019. It is a significant improvement over prior port work and deserves a much longer treatment.) It changes a number of things about my understanding of ports while a few things stay the same.

One thing that stays the same is that just flaring the ends of a port or providing an arbitrary radius isn't always a positive design change. Sometimes you make things worse. Another thing that doesn't change is that to truly optimize the port requires some advanced computer modelling, and there's no computational fluid dynamics tool that's easy to use for the DIYer. Or me for that matter.

So, I did the next best thing. I eyeballed it. Really. I took the port profile they derive through advanced computational optimization and just got as close as I could...I did this so that I could compare what's possible in a relatively short amount of time. Could the fancier port be improved? Probably, actually, almost definitely. Did it show enough improvement to be more than interesting for the purpose of this paper? Absolutely. Quite educational.

⁵ <https://www.aes.org/e-lib/browse.cfm?elib=20683&fbclid=IwAR3Sx7n9GLnUjYOayBdbWzXBo7yt5Z7KFSmVQLFLn9wTMkYLSDPmdCxKBVY>

(Open Access Paper, no fee/membership required.)



So what does this port look like?

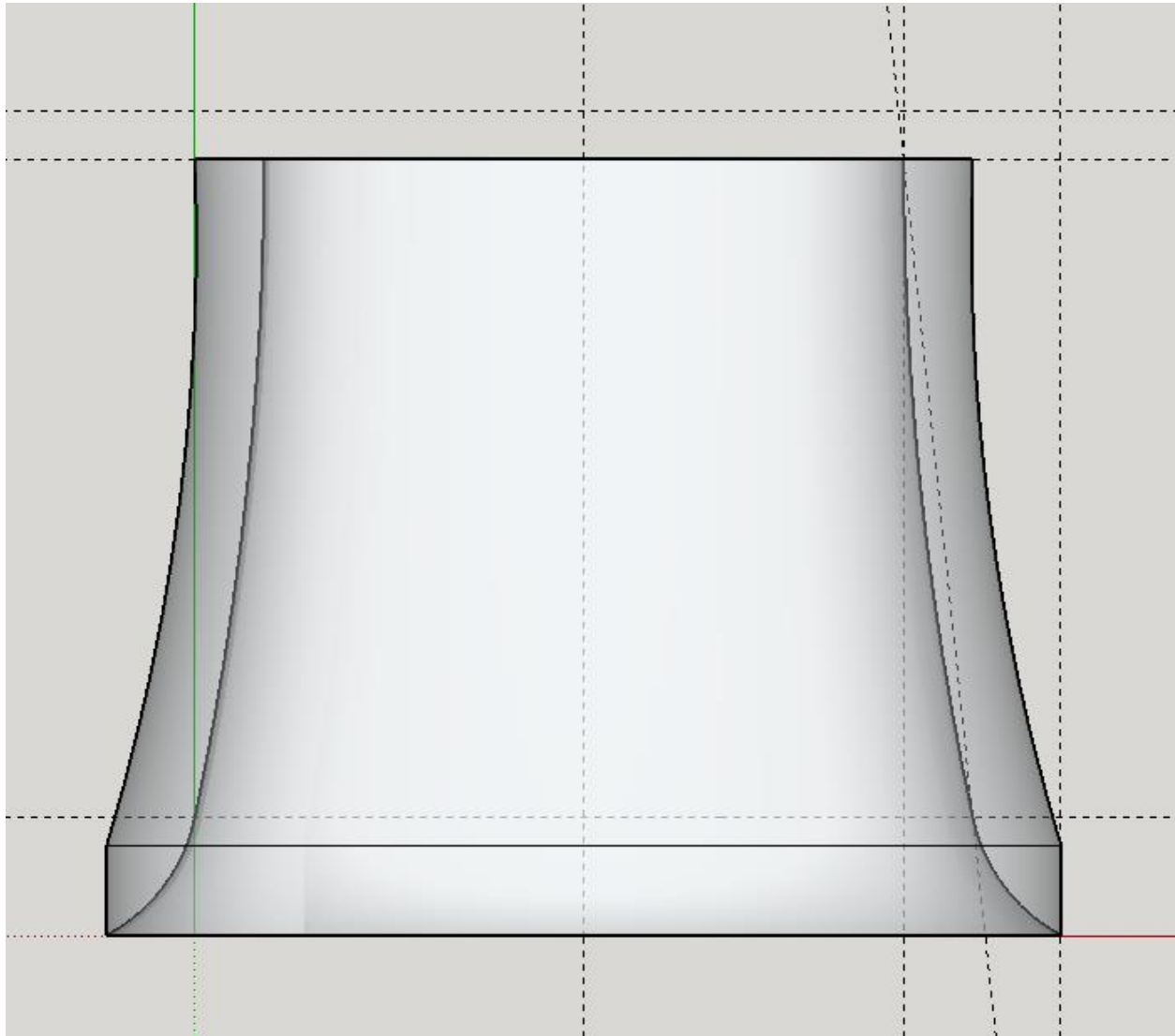


Figure 9 Swoopy Port (Well half) Profile, I printed it in two sections and glued the whole port together.

The port follows the rough shape in the Bezzola/Devantier/McMullin paper. I was guided by an older work in AES that showed the benefits of gradually tapering from the center of the port at approximately six degrees, and then putting a radius to blend to the speaker wall. That radius is pretty important, and I'm not actually sure I got it right, but that will be the subject of a future paper. I did get it right enough to drastically outperform the straight port. I will eventually have to provide a part 2 to my original port distortion/overload paper, because the results are too good to ignore.



Myths and Silliness

As I mentioned in the introduction, I've seen a lot of myths and silliness espoused to transmission lines over the years. I'm going to paraphrase a number of them here.

-Transmission lines are better in the time domain.

This one has the potential to have **some** amount of truth to it. But man, it's a stretch. At the end of the day a TL is a 4'th order system, where the line output is contributing to the response. As a result, it's going to have the phase/time domain response of a 4'th order system, and that's the same as a bass reflex. You do have the option to tune the "knee" of the rolloff with the line stuffing in ways that you may not be able to do with bass reflex, but as previously mentioned that comes at the expense of sensitivity and efficiency; and is a bit of a fool's errand. Tuning this knee could give you a lower phase angle change/group delay variation through the low end of the speaker...but the only way to do it is by lowering sensitivity.

-The larger terminus is more efficient than a port.

No....it's not. It's just not....velocity will be lower than the port, the same amount of sound pressure is generated and the electrical input power is likely very similar.

-The transmission line terminus inverts the phase of the rear wave.

No...it's a resonant system, it's more complicated than that.

-Transmission line terminus output is a ready to launch wavefront because of the larger surface area than a port.

That's just a word salad that has no meaning. The wavelength at typical bass frequencies is many feet, and the terminus dimensions are in inches. There's a number of others...but they just devolve into pure silliness.

-Bass reflex boxes have one note bass, transmission lines are inherently more detailed.

When you look at the measurements for the systems, they are both 4'th order rolloffs. I'm not saying they sound the same, because there are some clear differences, but this to me is an indictment of comparing a poor bass reflex design with a strong response peak to a transmission line. If you made the transmission line with a strong response peak (very difficult to do in practice once you start adding line stuffing) they would be saying the same thing.



Measurement Results

Straight TL vs. 2 Segment TL

The first thing I wanted to do was repeat my measurements I took of a multi-segment line vs a single segment. Previously I used a small 2.5" "subwoofer" driver and a 3-segment vs straight line. This time I built a full-size straight line for a 6" woofer. The idea was to isolate the variable of a multi-segment line as much as possible. Both lines had the same physical length, same cross-sectional area. There are two differences, besides single segment vs. 2 segments....to maximize material usage and minimize cost the straight line has a square terminus while the 2-segment line has a terminus aspect ratio of 1.72:1.

Doing a ground plane measurement on the straight TL is out of the question, the line length would require a long measurement distance, or the time/distance differential of the separate sources causes all sorts of issues. I can't drive a 6" woofer hard enough to get good measurements at the 10+ meter distance I would need to use. I had to do nearfield measurements of the terminus for the comparison. Since both are the exact same cross-sectional area, there is no need to do a correction based on size.

I painstakingly cantered the microphone using callipers and used a laser level to make sure the tip of the microphone was exactly at the mouth of the terminus for both speakers. When doing nearfield measurements a few mm can easily make a 1dB difference. Considering the low frequency (below tuning) output matches so well, I suspect the measurements are directly comparable.

Terminus Output



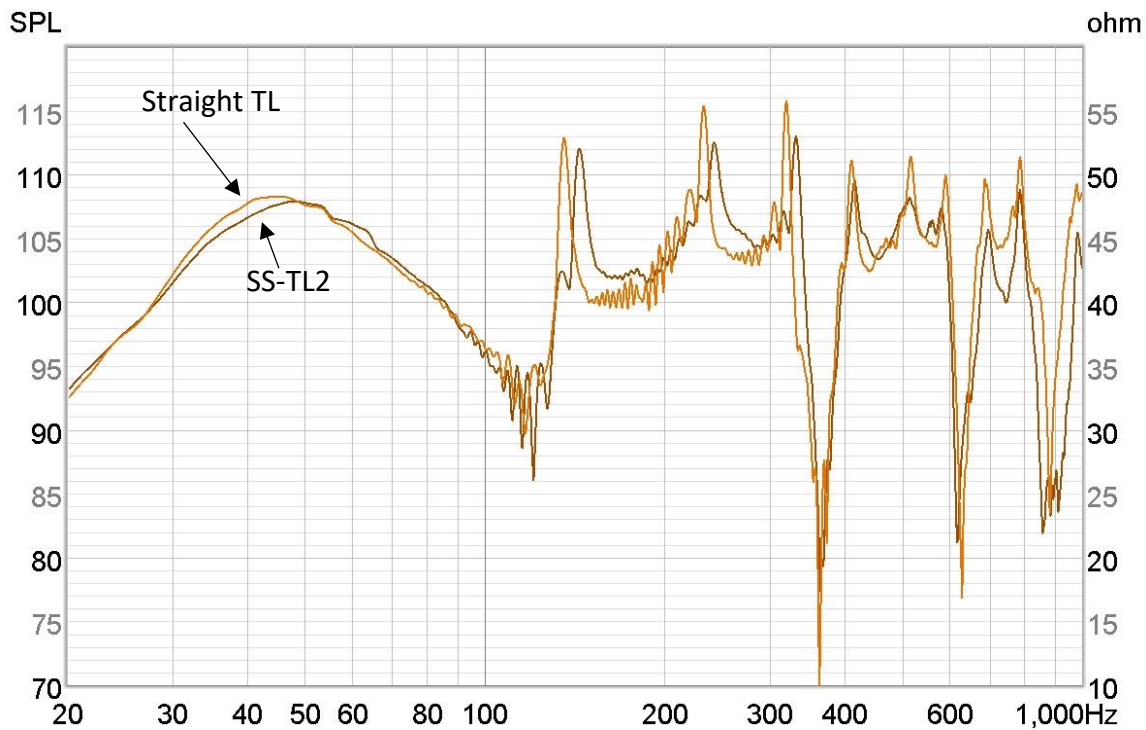


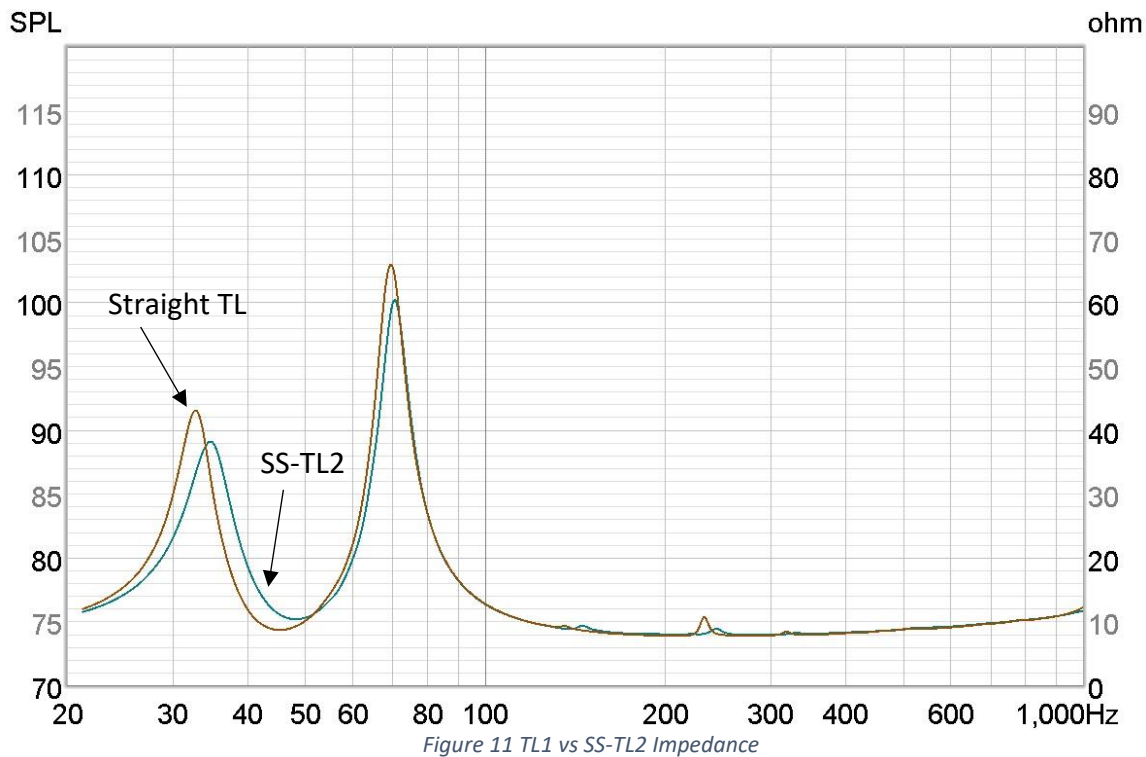
Figure 10 Straight vs. 2 Segment Transmission Line Terminus Output, Nearfield.

Two things jump out at me right away. The fold has shortened the effective line length, and the output is lower by about .5-1dB. This amount of bass lost with one fold is significantly less than the 3 fold smaller line, but it is there. The shift in effective line length also confirms that you can't just fold these things willy nilly without impact even at the fundamental tuning frequency. Based on my experience with quarter wave-based designs, I'm not surprised...this is yet another confirmation of what I have seen before. The impact of the fold is different for every design, some of it is due to the folds themselves, and another portion of it is probably attributed to enclosure losses. The walls of the enclosure aren't infinitely stiff and since the unsupported distances in the panels of a folded enclosure are probably different than those of an unfolded enclosure you are seeing the impact of both the fold and different enclosure losses.

There's a second way to look at it too....impedance. When Q of a system drops due to losses induced the impedance peaks drop. Some folks over the years have advocated for stuffing the line until the two peaks merge into one...but by the time you've done that you've created a very lossy sealed enclosure.

What did I measure for these two designs?





The impedance curves of the two speakers are different indicating the two enclosures are not equivalent. The 2-segment line has a lower Q for the lower impedance hump, and you can clearly see the difference in effective length, the two impedance minimums are at a different spot.

The takeaway here is that you absolutely cannot fold the line with impunity, and my strong suspicion (again based on experience, these last few papers plus years of building enclosures like this) is that more folds = higher losses and worse performance. Fold with extreme caution...and limit yourself to only one or two segments.

[Straight TL, Terminus Output Offset/Full Length, a question of Q](#)

When I published the first of the previous transmission line writeups a professional working for a pro-sound company reached out via DM and said something to the effect of “yeah...they may have the same response (ported vs TL) but they still sound different because the terminus output is a very different Q.”

I then remembered discovering this on my own years ago doing a transmission line design with a Vifa XT woofer. It was a good reminder though. So, I measured the output of the terminus of the woofer at the end of the line and offset roughly 1/3 the length of the line.



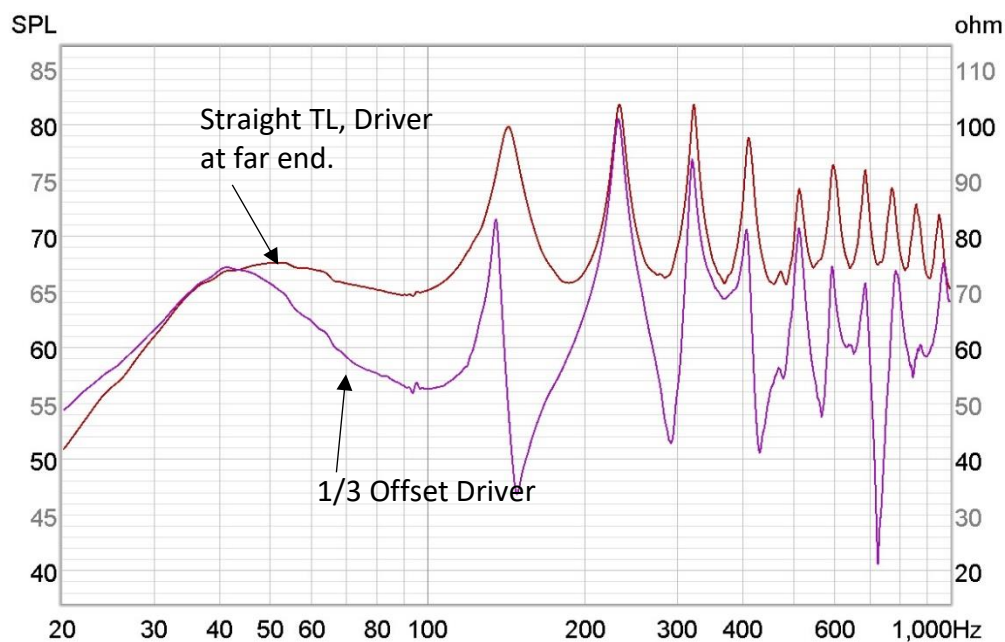


Figure 12 Offset vs. End Terminus Output

You can see in the two measurements how much effect the driver placement has on the terminus output. Remember how King's presentation claimed the two designs were equivalent, but the TL had higher sensitivity above tuning due to the terminus output? Well...if you do an offset line, you lose that sensitivity⁶, the Hornresp simulation and the physical measurement showed that the terminus output changes, as does the tuning frequency.

It would be nice if they always cancelled each other...but I doubt that's the case.

MLTL vs. BR vs. TL

The next thing I did was take the MLTL, BR-1, BR-2 and SS-TL2 designs (that would be the Mass loaded transmission line, straight port bass reflex, swoopy port bass reflex and traditional folded straight transmission line) and subject them to several tests. I measured the terminus output nearfield; I measured the impedance at voltage drive levels of 1-2-4-8 and 12VRMS and I measured the output at those same drive levels at 2m using the ground plane technique. I won't present all of the measurements here (there were over 300 made) because many of them are repetitive in the story they tell and were used as checks to verify each other.

Baseline Response Comparison

⁶ Again though while I'm generally pro-higher sensitivity, using delayed output, broad band doesn't seem like the right way to do it. That's in direct opposition to general consensus of high fidelity sound.



The first thing to check was how close I got the overall response, the goal being that they had similar tuning frequencies. It would be too much to ask for them to be exact....but I wanted them to be within a few Hz.

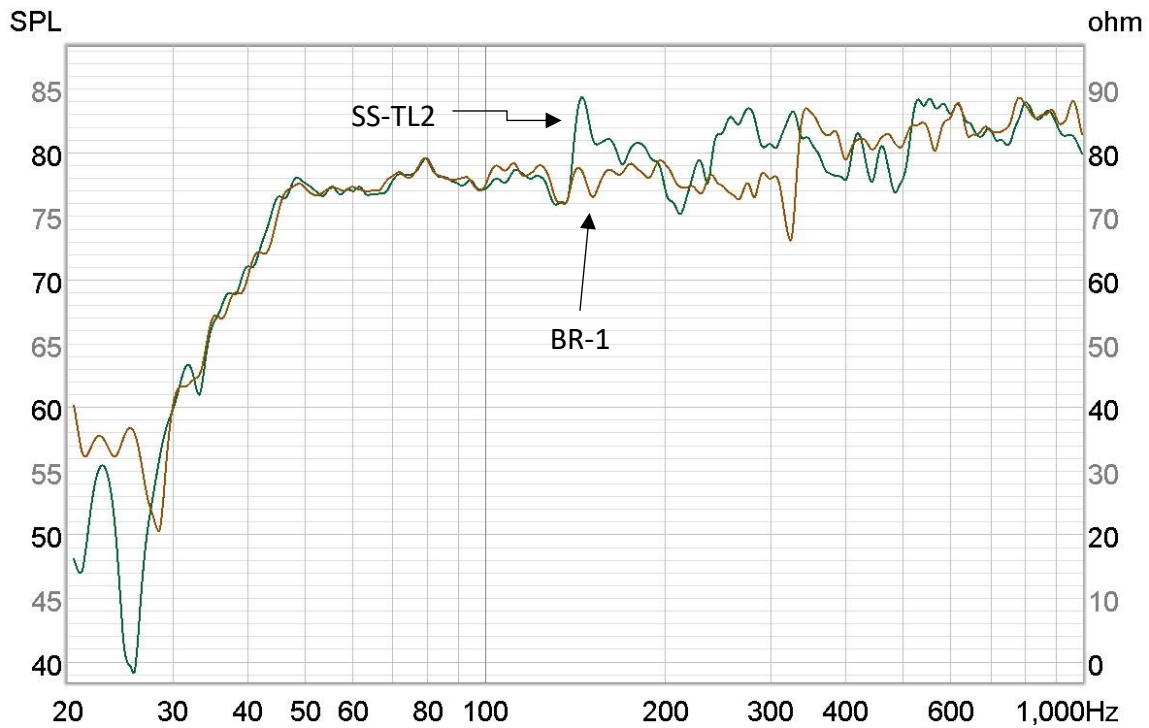


Figure 13 BR-1 vs. SS-TL2, ground plane, 1V

The match between the straight port bass reflex box and 2 segment transmission line is quite good, with practically identical bass response. The line reflections of the transmission line are quite evident in the high Q peak at ~150Hz.

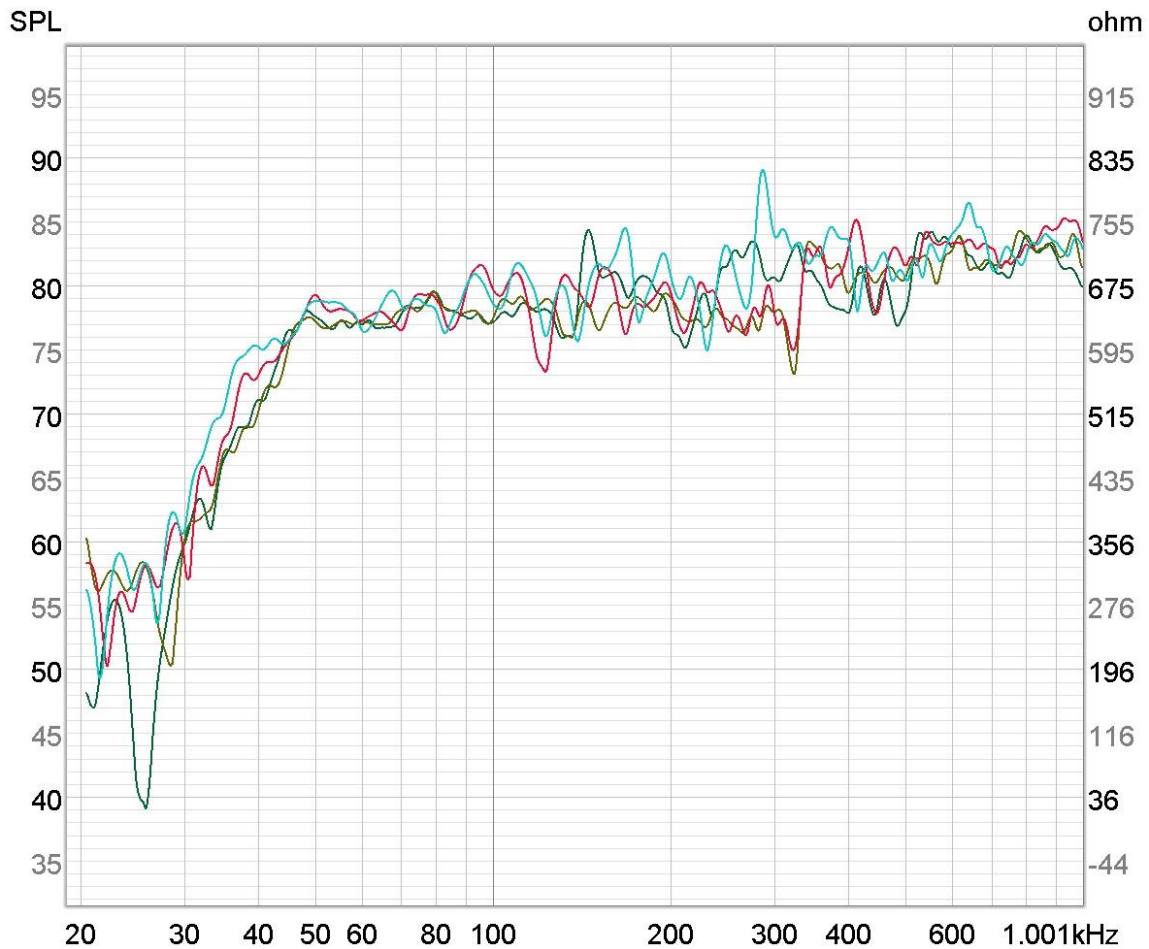


Figure 14 SS-TL2 (dark green), BR-1 (light green), BR-2(pink), MLTL (light blue)

Comparing all alignments shows reasonable agreement between them...so let's start looking at the comparisons.

Compression

First let's look at compression over drive level. For each of the 4 systems I took the 1V and 12V measurements for comparison. The 12V data was reduced by 21.6dB to level match it with the 1V data, and the results were divided. That gives compression for the speaker as a positive number. I zoomed in on the range from 35Hz on up, at 1V drive level the low frequency measurement is subject to variation from external noise such as cars, wind, etc.

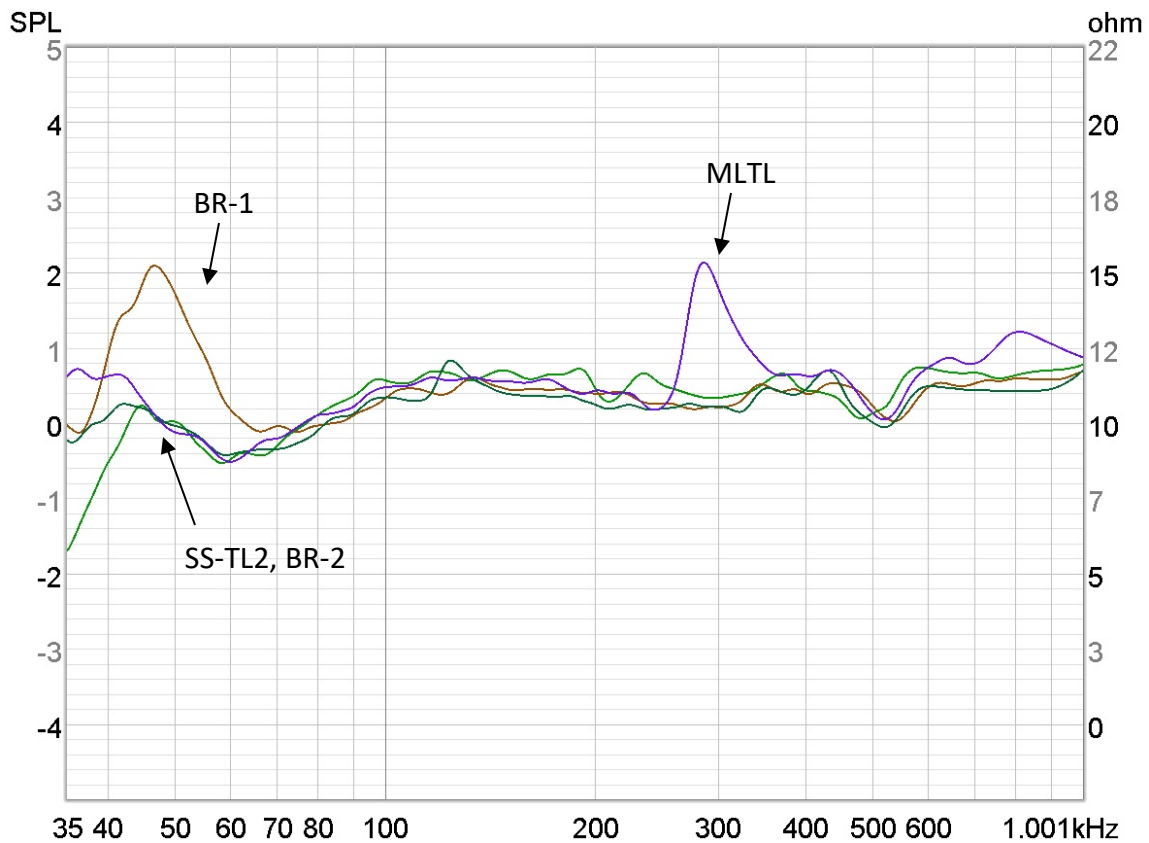


Figure 15 Compression, Ground Plane

The measurements showed that the BR-1 box had by far the worst low frequency compression...a hair over 2dB for the 21.6dB drive level change. The changes for the MLTL, BR-2 (swoopy port) and 2 segment transmission line were negligible.

Interestingly there was a significant amount of compression of the 2'nd line resonance for the MLTL. You can see this by looking at the response of terminus near field in comparison to the ground plane 2-meter measurements.

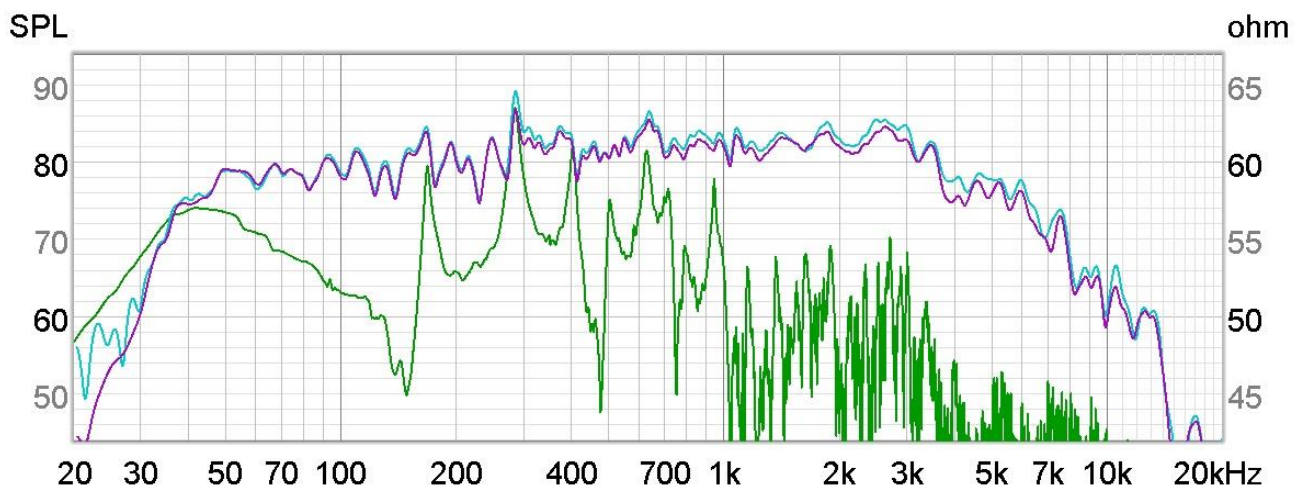


Figure 16 MLTL Resonance and Compression (Blue = MLTL @ 1VRMS, Purple = MLTL @ 12VRMS-21.6dB, Green = Terminus Nearfield).

I'm not sure what could cause that, I double checked it by repeating the measurements and saw the phenomenon both times. I do know that, in general, I don't want my frequency response changing by volume in an uncontrolled fashion. I'm all for a well applied dynamic EQ, but I'd really like the speaker system to be as stable as possible. You can also see in this measurement the impact of the external noise floor in the low frequency measurements...the purple trace is the 12V measurement and is much cleaner below 30Hz. I don't have the time to build a second MLTL for a different driver to see if this is repeated, but it is something to watch out for if you do build one of these.

Another way to look at the compression was to examine the terminus/port output near field. This is a challenging thing to do, you need to measure nearfield enough to keep leakage from the active driver from corrupting the measurement, but nearfield measurements are shockingly loud. At 12V, I calculated that if my measurement microphone was at the plane of the port or terminus SPL's of >150dB at that location were possible. I built a spacer so that I could set the microphone at 50.8mm/2" from the port/terminus. I still can't use a UMIK-1, or even iSEMCon for this, but it does make it possible for me to use my Josephson C550F high SPL microphone.

For this test I'm looking at the output of the port/terminus compared to itself, so there's no need to scale the results based on SD. I had a couple of folks tell me that I should have done that in the last paper....not sure why...you scale when you're summing two sources or making comparison between the two responses directly. In this case I'm not doing either of those...I want to see how much each one changes over input amplitude. Basically, within each plot the two that overlap each other best are the best performers. If they deviate from each other, that's not good, and something we want to avoid.



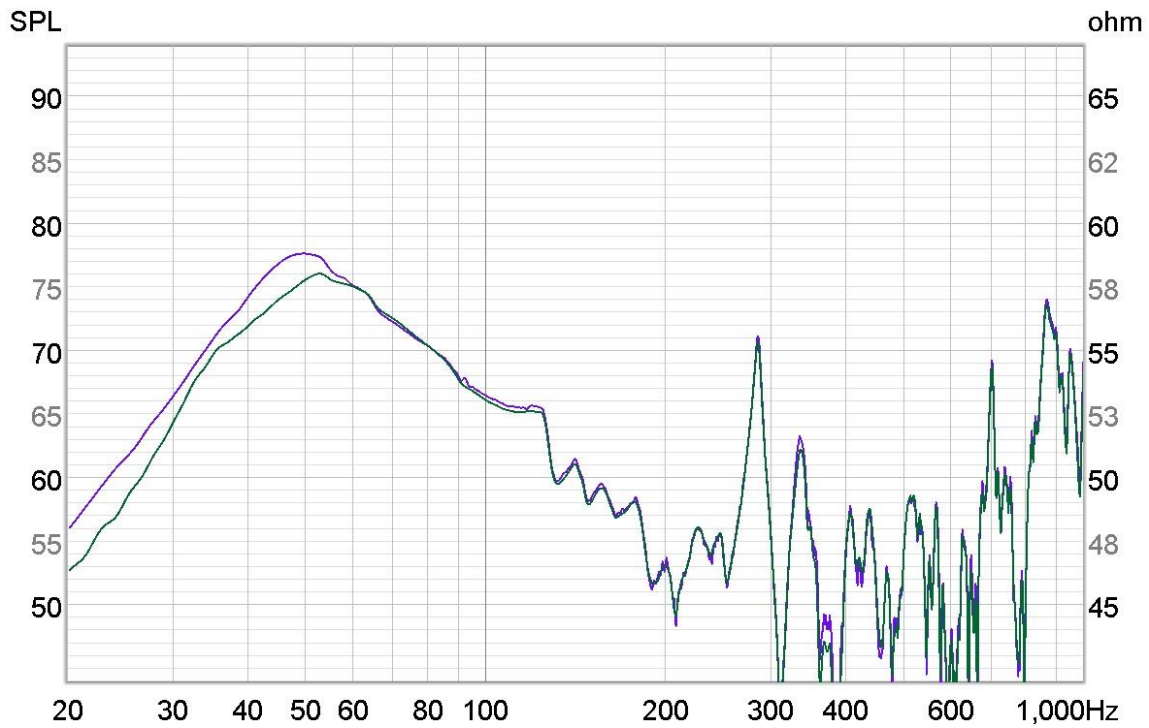


Figure 17 BR-1 Port (Straight walled port) Response change with Drive Level (12V/1V), 12V response scaled by 21.6dB

Eeek...that's a fair amount of response shift....and clearly the port compression is the cause for speaker response changing in the ground plane measurement.

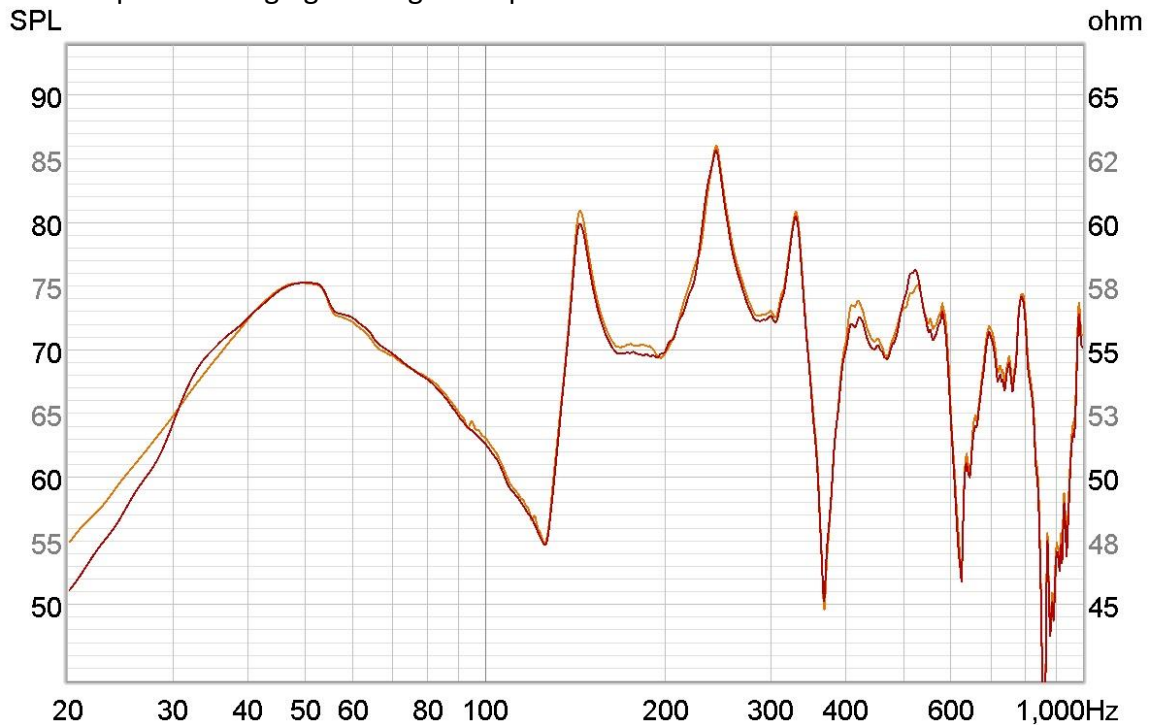


Figure 18 SS-TL2) Response change with Drive Level (12V/1V), 12V response scaled by 21.6dB



The two segment TL performs much better than the straight walled port. You can see some compression starting to set in below tuning frequency, but at line tuning it's quite solid.

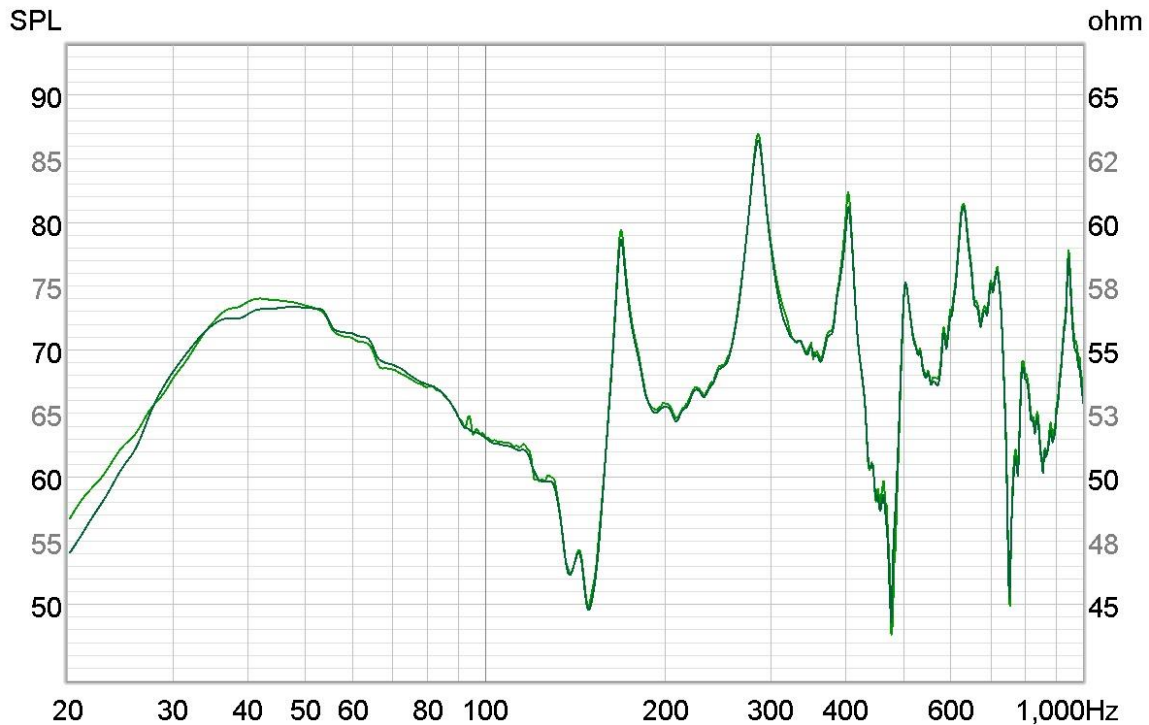


Figure 19 MLTL Terminus Response change with Drive Level (12V/1V), 12V response scaled by 21.6dB

You can see a bit of compression setting in at tuning frequency for the MLTL. The CSA of the terminus exit is about 1/3 of the SS-TL2. This means a higher velocity at the terminus. This is where the nearfield technique can be so powerful because this wasn't as obvious in the ground plane measurements.

So...that leaves the BR-2 port. How did the swoopy port do?



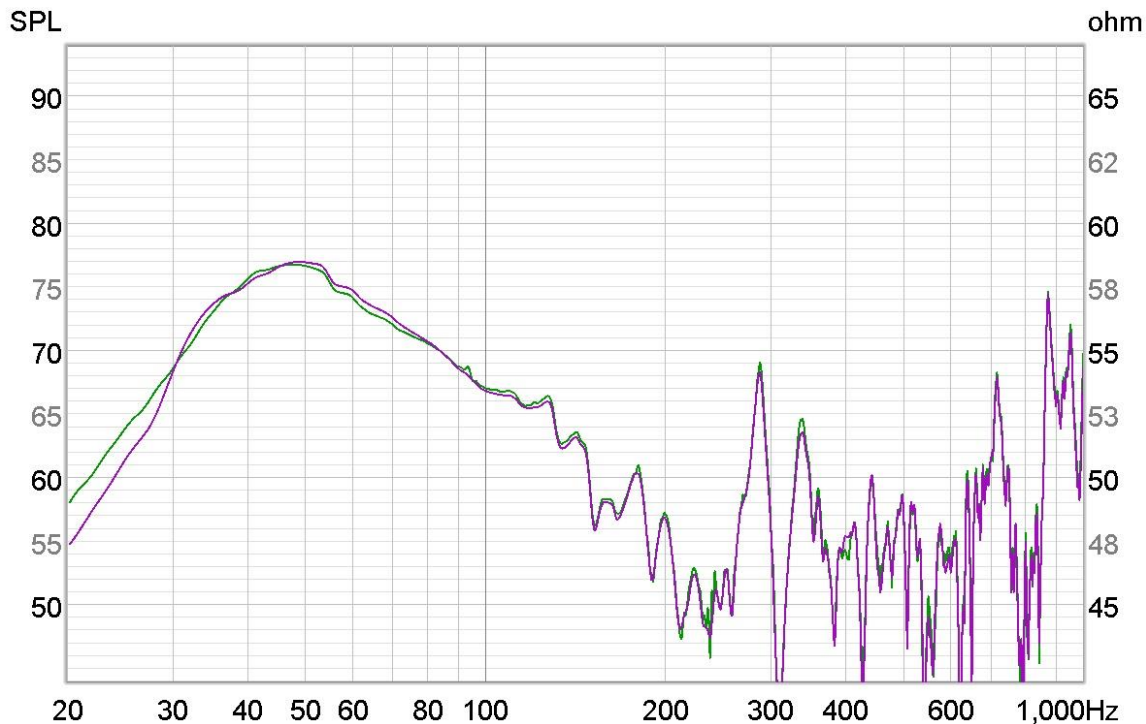


Figure 20 BR2 Port Compression, Response change with Drive Level (12V/1V), 12V response scaled by 21.6dB

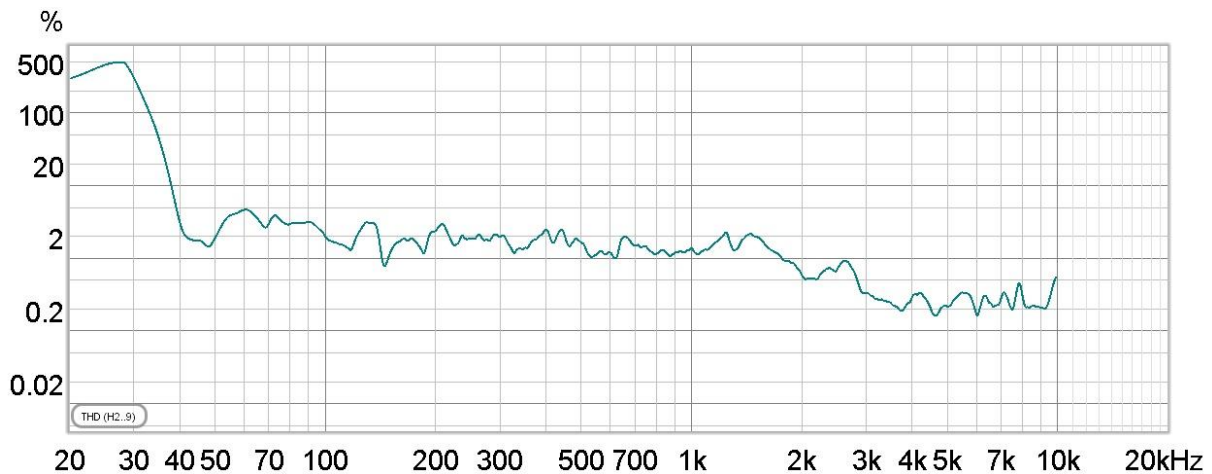
Now the bass reflex design compression performance can equal the 2 segment SS-TL2, and comparing the HF leakage the BR design is significantly higher performance than the transmission line terminus. The higher order line reflections are higher in magnitude than the fundamental, in the bass reflex port they are lower, and in the 200Hz-400Hz region significantly lower. This means I get all the output, without the high frequency resonances/artifacts that could be quite audible. One of my takeaways on all of this was...if you are going to make a TL type design, put the terminus on the back, making that high frequency leakage/resonance less audible.

Distortion

How do the designs compare for distortion performance? Well, the 1 and 2V sweeps aren't particularly useful here. In the previous paper I didn't include distortion measurements because I wasn't convinced it was a fair comparison. After reviewing the data, making multiple sweeps over multiple days with different levels of background noise I'm comfortable looking at the 8 and 12V sweeps for comparison's sake. I'm marginally okay looking at the 4V sweeps, but the background noise for the 1 and 2V sweeps is just too high.

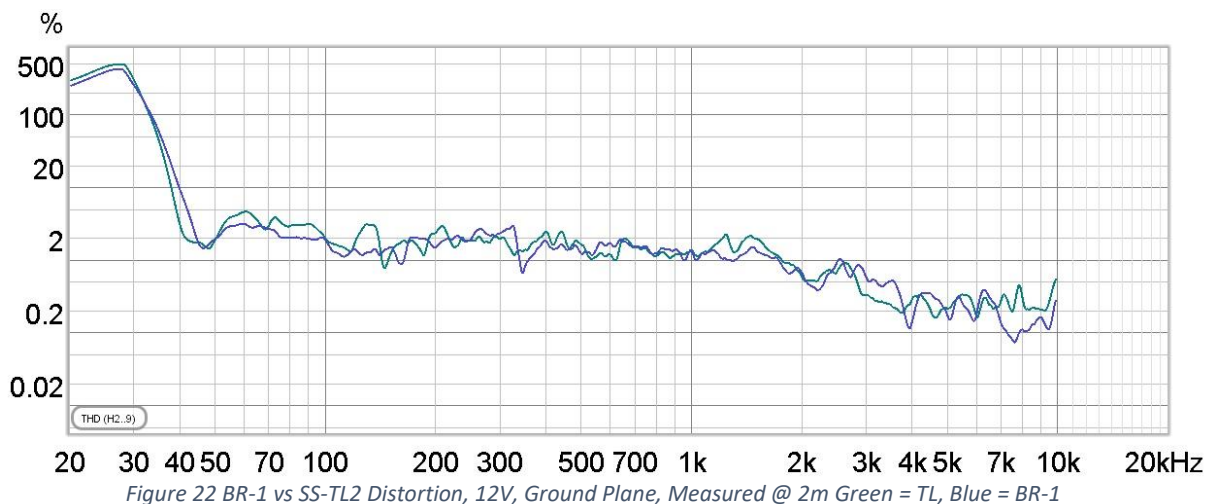


As a baseline let's look at the SS-TL2 distortion, swept at 12V.



Distortion peaks at 4.6% above tuning, at 60Hz. For a driver at this price level with a relatively standard motor structure, this is pretty good performance. A 12V sweep is shockingly loud.

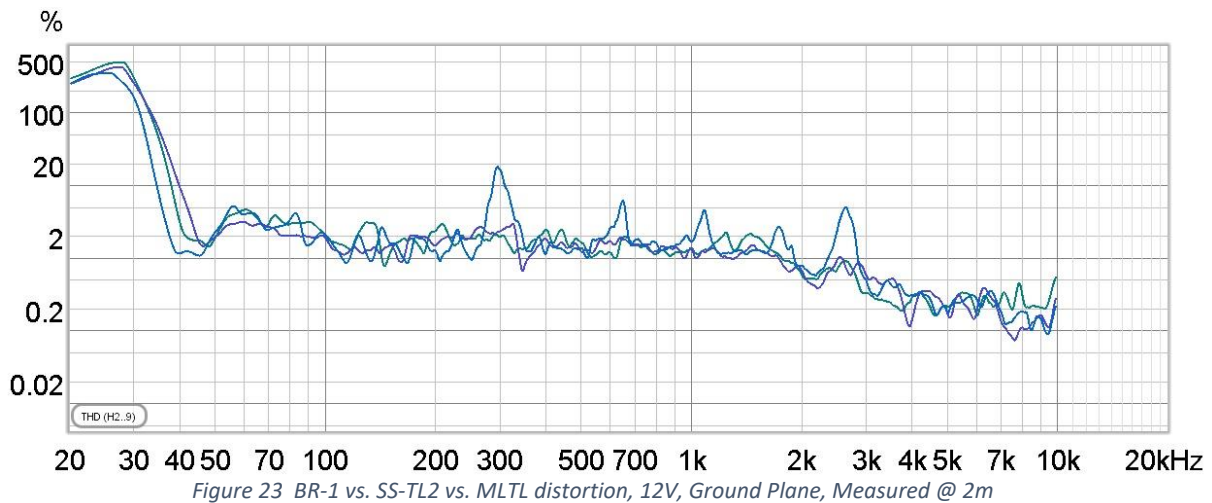
How did that compare with the BR-1?



Even with the compression of the BR-1 straight walled port the distortion performance is slightly better above tuning for the bass reflex box. I'm not ready to jump up and down celebrating this, since I suspect if I EQ'd the output to match the transmission line the distortion would jump up enough to be equivalent, possibly even worse than the TL. Note that neither box had stuffing in it for either of these measurements.

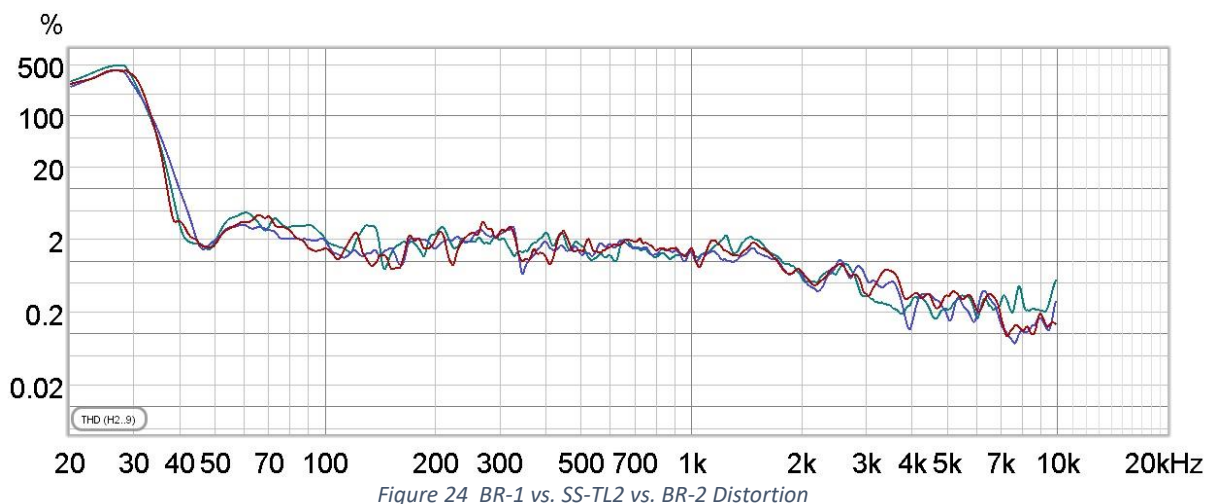
How does the MLTL compare?





Low frequency distortion performance is similar for all three...but weirdly the line resonances show up as distortion peaks for the MLTL design, when they don't for the SS-TL two segment straight line. Both of these had their terminus at the base of the speaker on the back, so this is an unexpected result to be sure. To me the big takeaway here is that, yet again there is another operational difference between an MLTL and a bass reflex box, and again it's not a benefit. Folks using line-based speakers for low frequency performance need to be aware this can happen, and performance should be verified with measurements. Another thing to keep in mind is that 20% distortion at 300Hz is **PLAINLY** audible.

Now how did the swoopy port do?



To keep the plot a bit simpler I left off the MLTL distortion plot for now. As you can see...the distortion performance is on par with the SS-TL2 (and the BR-1 for that matter) but with the benefit that the compression of the BR-1 at these drive levels is effectively eliminated. The bass is back, and distortion is still good.



MLTL, BR-2 and Stuffing

Next, I took a look at impact of stuffing. In a previous DIYRM writeup I looked at different stuffing types and densities and the impact on performance for a bass reflex system. I pointed out that the low frequency alignment changes were minimal for stuffing, no matter which type I used, and over a wide range of stuffing densities. I only got to a significant shift when I used so much stuffing it was difficult to get the driver into the box...I had to force it down compressing the material tightly.

Is that the case with the MLTL box since those terminus reflections are so problematic? I hoped so, because that would make MLTL design easier removing a variable from consideration. Unfortunately, that wasn't the case.

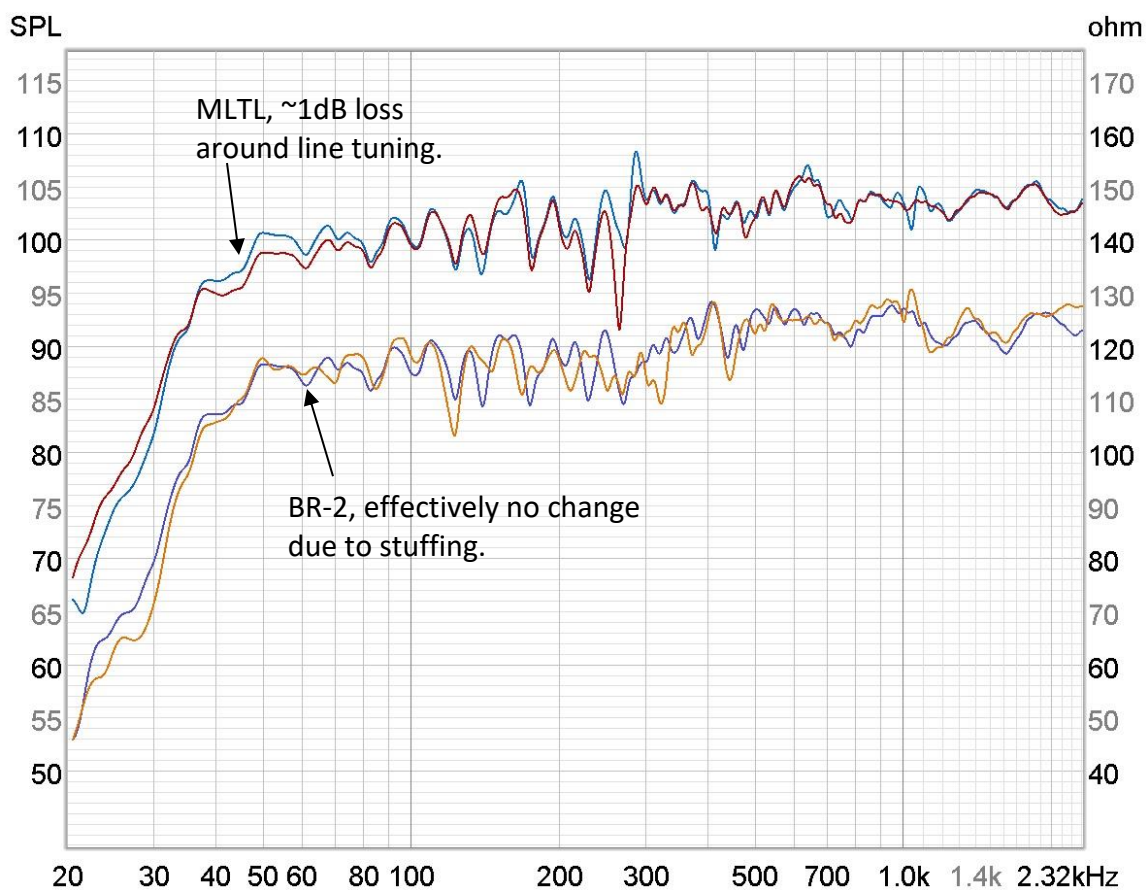


Figure 25 MLTL With/Without Stuffing vs. BR-2 With/Without Stuffing, BR2 offset by 12dB for clarity.

The MLTL lost about 1dB of output with stuffing added. Here's the real kicker...all the stuffing was added in the widest/closed end of the line.

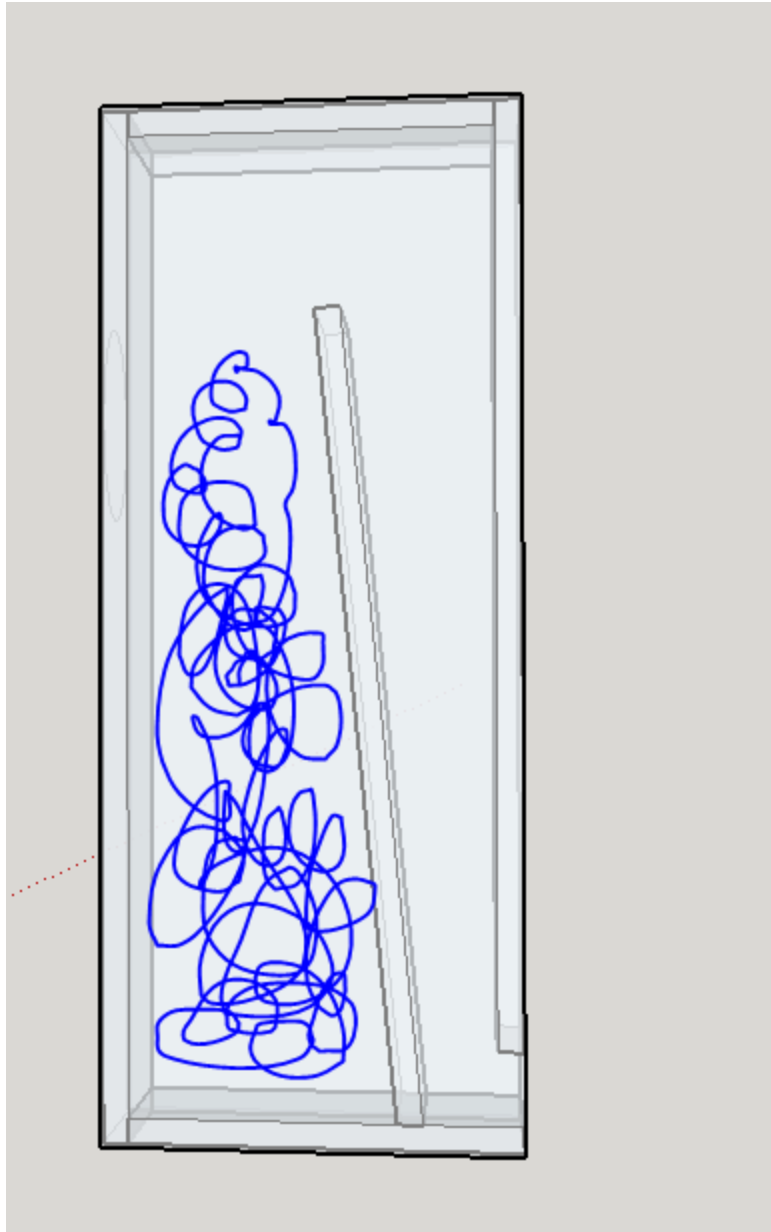


Figure 26 Stuffing Location, Top shelf graphics by me. Stuffing density not drawn to scale.

I could more easily see the bass alignment changing drastically if the stuffing is between the driver and the terminus...but was not quite ready for this outcome. I used the exact same amount of stuffing between both enclosures, literally, it was the exact same stuffing, I took it out of the MLTL and put it into the bass reflex enclosure. So now, we know for sure that our low frequency alignment depends on stuffing level *and* driver location (and all those other things, like line length, taper, cross sectional area...etc...)

I would also point out that this is another reason why I don't believe that the two designs are equivalent. Behaviour this different is a strong indication that they need to be kept separate



when thinking about resonant designs, and while the low frequency 4'th order rolloff is the same the operational mechanism isn't.

The next thing I looked at was the stuffed vs. unstuffed line and distortion.

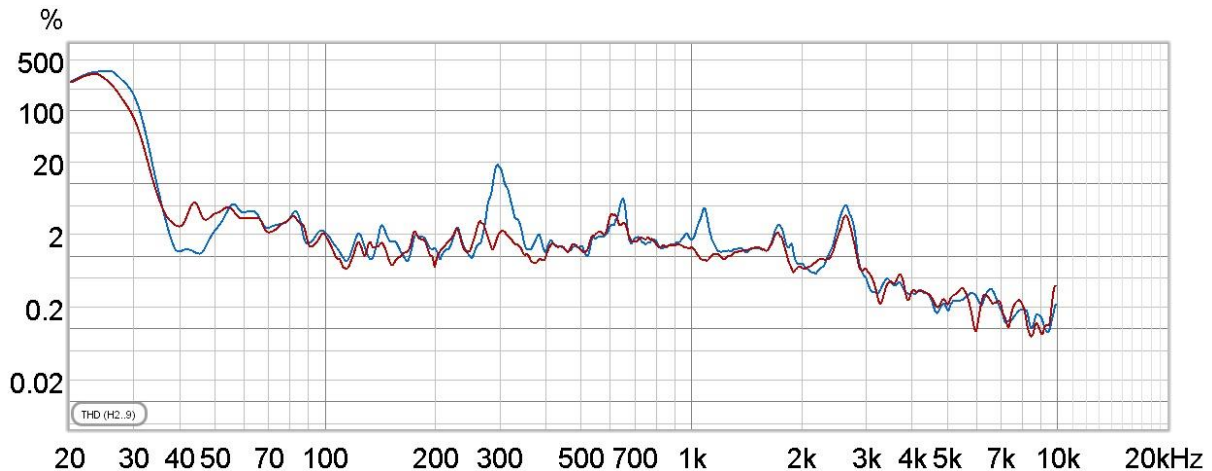


Figure 27 MLTL, stuffed and unstuffed....

Stuffing the line did reduce most of those distortion peaks, so it is something that is manageable. But...to reduce those distortion peaks means we've lost some output which we don't have to do for a bass reflex design.

Time Domain Performance (When I say stop, I mean...STOP.)

There's a lot of ways to look at time domain performance for systems. We can look at the step response, the impulse response, and then there's several fancier views like cumulative spectral decay plots (waterfall plots), burst decay plots, and spectrograms.

Before I show any plots from these, I'd like to go over some of the errors that I see when people try to demonstrate performance by using these metrics.

First, the most common is using a cumulative spectral decay (CSD) plot from a measurement that has a lot of external error in it, often with ludicrous processing applied. This yields fancy looking plots that mean nothing. You see these long decay times and you have no idea if those are reflections off external objects (buildings, cars, trees) etc....or a function of the speaker or, a function of the processing applied. How the windows are set up make a huge difference. At this point if I see a CSD and someone is claiming that it shows better bass performance from a design, I ignore it completely. I would venture to say that the only valid use for CSD is high frequency resonances, like cone breakup on a woofer. Even then the processing issues must

still be considered. Bill Waslo has the best writeup on this, I would direct you there⁷.

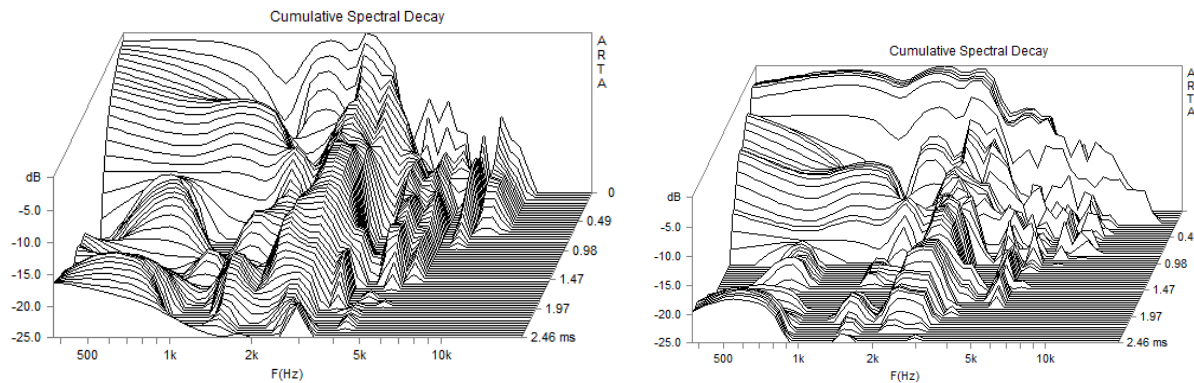


Figure 28 Two different CSD's, same speaker, same measurement, but different settings. This and oatmeal raisin cookies are why I have trust issues as an adult.

Instead, I think a burst decay measurement is much better for looking at bass frequency time domain performance. This measurement takes the impulse response measured and uses the information to determine how long a shaped toneburst would ring. There is no processing/gating window moving along the measured impulse response so the display is less effected by the processing settings. You can make two different CSD's look very different based on processing settings even though it's the same measurement. Which one is valid? Both of them, but it's likely neither of them is telling you the frequency vs. time information you think it is. In a burst decay measurement, it's much harder to make the results different based on processing settings and is more useful in seeing differences in low frequency time domain performance.

So, I compared three burst decays....BR-2, SS-TL2 and MLTL, all from the unstuffed box measurements. Things change, but this sets a baseline since the stuffing is reducing the impact of the resonances that are present. Enclosures that have fewer time domain issues will be easier to deal with...and the enclosure with the fewest time domain issues was the BR-1/2 (nearly identical performance) boxes.

First, I put a line at 10 cycles of the burst decay at low frequency. Both the SS-TL2 and MLTL have resonances that approach that time period....while the BR-2 stops making sound faster.

At higher frequencies the MLTL is the worst of the three, and I don't consider it close...you see multiple ridges lasting over 20 cycles while the BR-2 has far fewer. I've highlighted that area with red ovals on the plot.

⁷ <https://www.libinst.com/wattlar.htm>



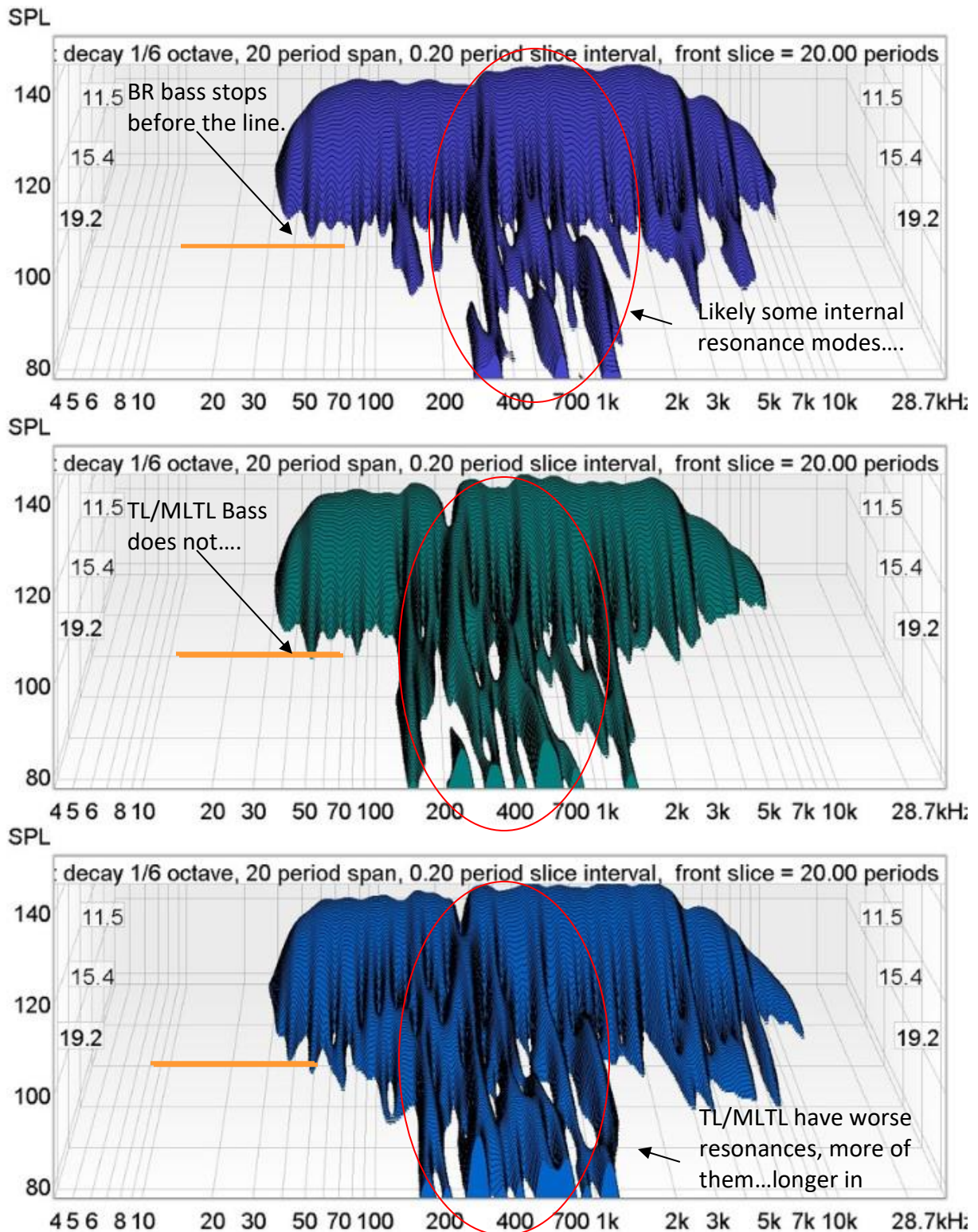
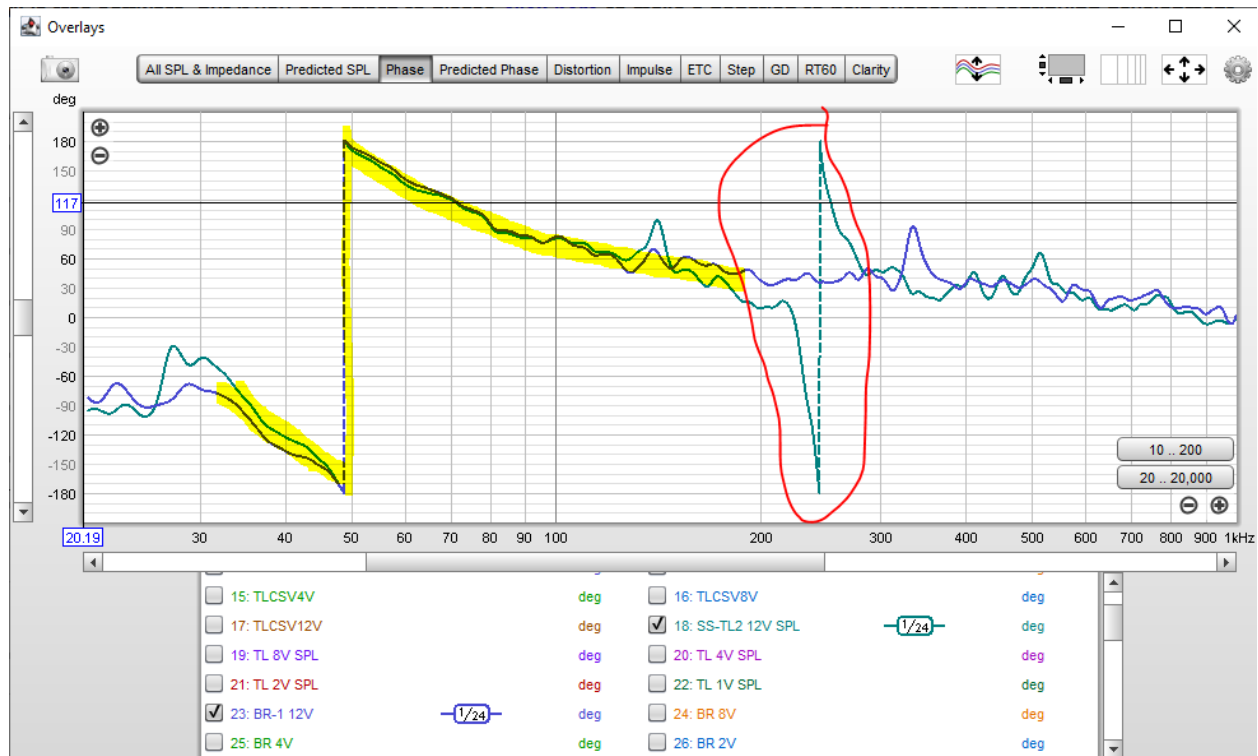


Figure 29 BR-2 (top), SS-TL2 (middle), MLTL (bottom) Burst Decay, Ground Plane Measurements.



To Minimum Phase, or not to Minimum Phase, that is the question.....

As soon as I published the paper comparing what I'm calling the SS-TL2 and BR-1 designs, a number of folks asked about phase response. I quickly obliged with the following measurement.



At first I concentrated on the plot highlighted in yellow...and I announced they were the same. I somehow missed, or didn't spot, or something, the phase rotation of the transmission line speaker.

Reviewing the data later I thought....oh my...that's not the same. That could mean there's some non-minimum-phase behaviour happening here. The catch was, I had taken all the measurements in REW without a loopback. I will hang my head in shame.⁸ So I took more measurements....and with a number of different programs because REW can be a bit tricky when it comes to absolute time references.

The first thing I did was fire up ARTA, and in dual channel mode look at the phase response of the system. It has loopback functionality and $t=0$ doesn't shift with each measurement. What I wanted to do was two-fold. First...I wanted to make sure I saw that same phase wrap with

⁸ Not....really.



ARTA, second I wanted to compare the minimum phase response with the measured phase response.

At this point it might be worthwhile for readers to go back and review what I wrote about minimum phase, linear time-invariant systems⁹. The short, no math version is best expressed something like this: The measured phase response of the system should match the minimum phase response calculated from the frequency response. If the two don't match well, then the system isn't minimum phase.

Now...that's as true as I can make words describing what I'm looking at without a lot of math. And if I put a lot of math in here, you'll probably¹⁰ leave. Because I wanted to be sure of the $t=0$, phase = 0 reference, I used ARTA and took a ground plane measurement of the MLTL design at a distance of ~2m. I then compared the measured phase response to the minimum phase response.

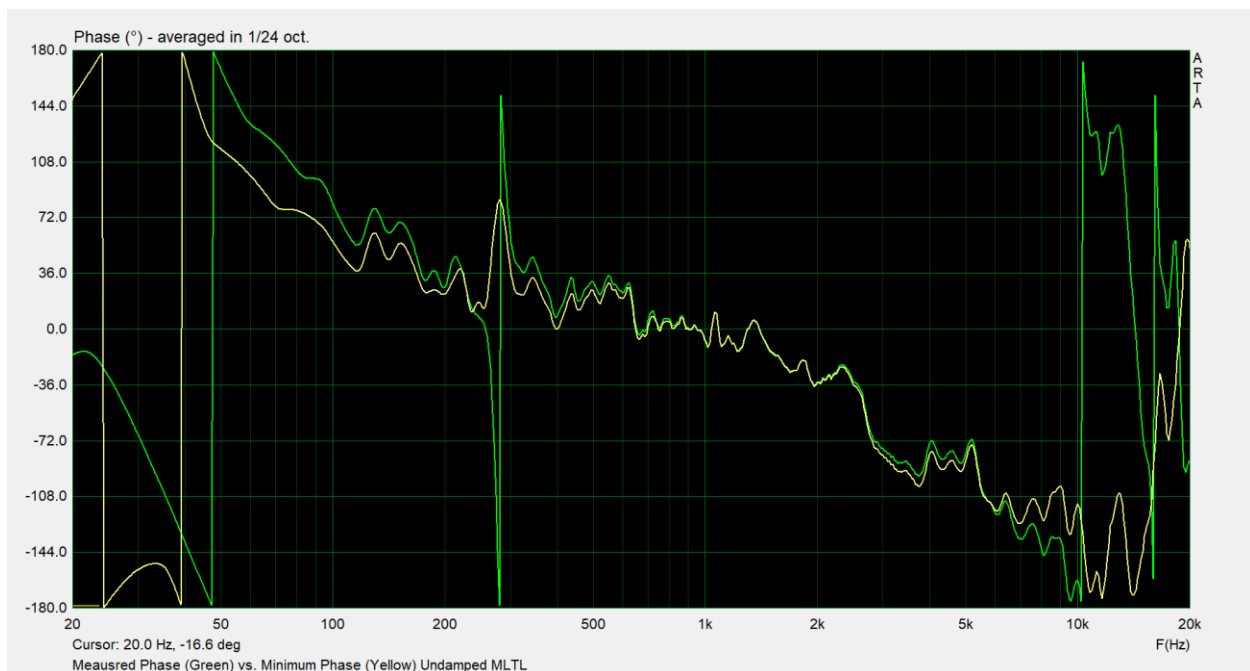


Figure 31 MLTL Phase Comparison, Measured Phase (Green) vs Minimum Phase (Yellow)

The minimum phase response has a wiggle at ~280Hz that corresponds to the frequency response having a sharp high Q notch. However, the measured phase does a full rotation there, and there's increasing deviation from the minimum phase response as you move lower

⁹

<https://www.facebook.com/DIYRM/posts/pfbid0vRM1z4wTgYzwkJgHVAk9qVsRY4uG4C3QRR7s1vi8qqvaDwkJ5xxzGGoMV1fN9U13I>

¹⁰ I prefer to be optimistic. Realistically, you'll definitely leave.



in frequency. I expect some of that is from noise in the measurement....at the high end when the woofer well into breakup mode you also see a deviation....but I fully expect that. I've seen it many times, and on full-rangers it can be even worse over a broader frequency range.

Next I measured the BR-2 box, again ground plane. And did the same comparison.

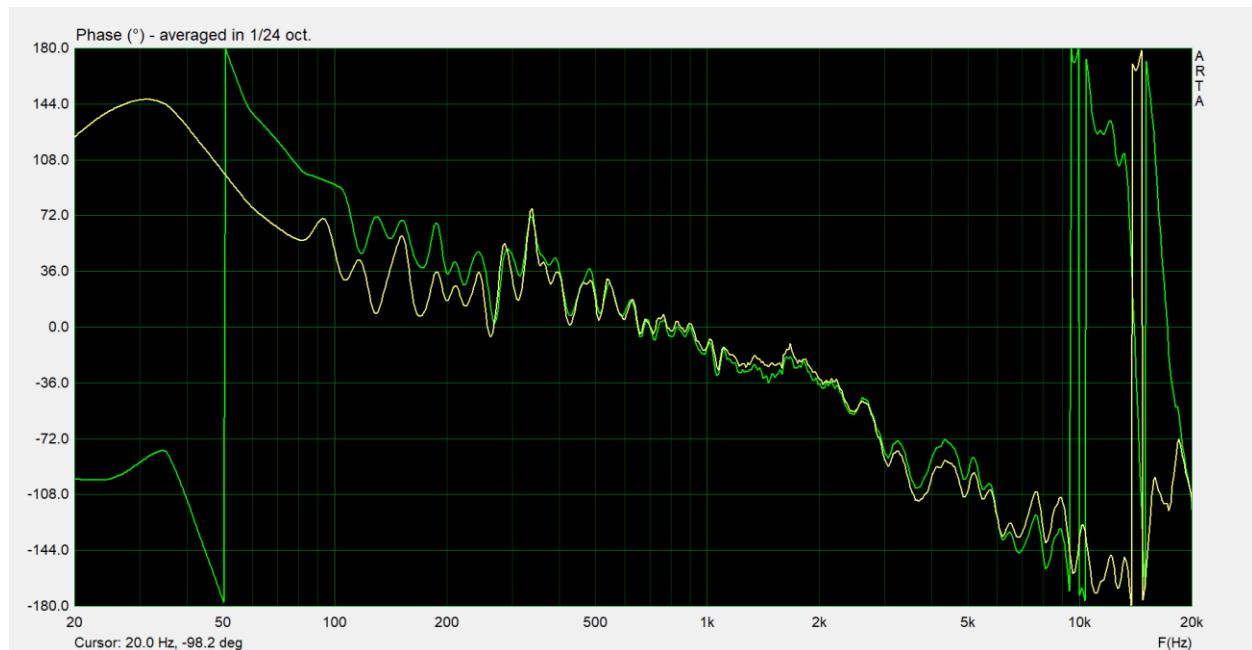


Figure 32 BR-2 Measured Phase (Green) vs. Minimum Phase (Yellow)

Notice there's no phase wrap. The BR-2 box, I would consider to be strongly minimum phase, while the MLTL is not.

To sanity check myself, I fired up SoundEasy (SoundMediumHard?) and did a series of similar experiments. First I did the same minimum-phase vs measured phase check on the MLTL design. SoundEasy has the added feature/complication of adding tails to the frequency response used for the minimum phase calculation. (It can be impacted by not having enough bandwidth at the extreme ends, and noise creeping into the measurements.)

It too showed the same thing. Which is good...because the systems should be equivalent to each other. One thing to note is that the excess group delay in that phase wrap region is shockingly high....around 45ms. Plainly audible.

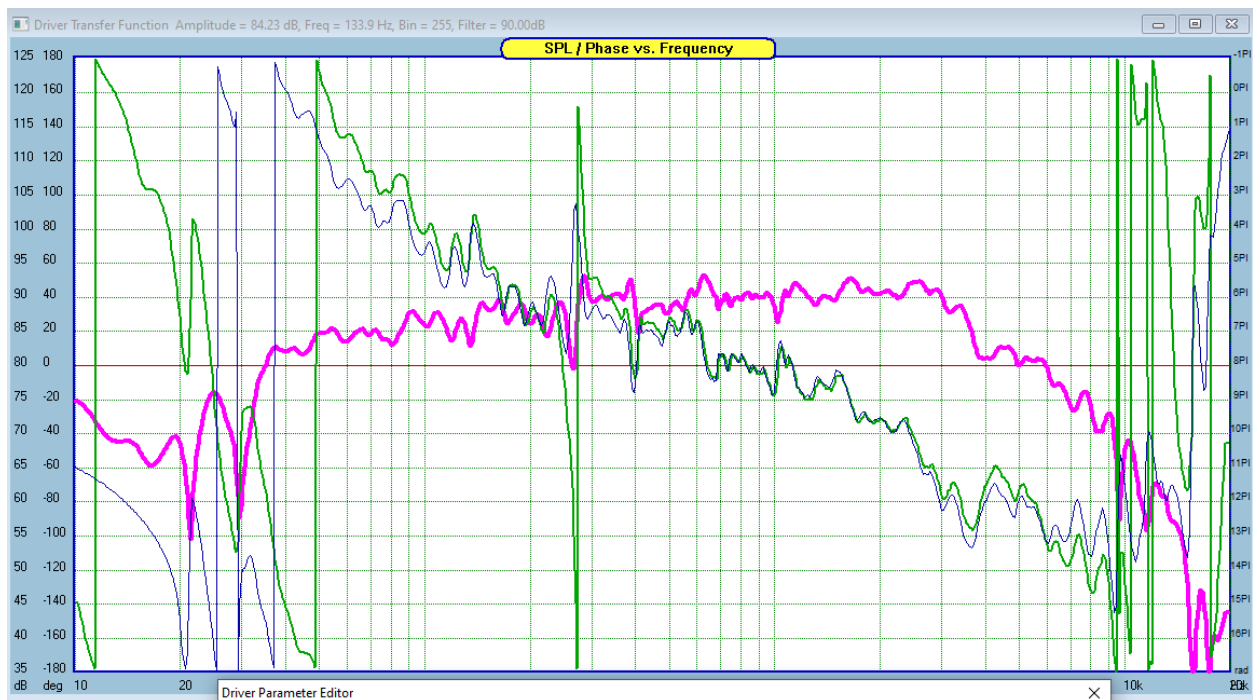


Figure 33 MLTL Ground Plane 2m Sound Easy (Blue = minimum phase, Green = measured phase, pink = frequency response)

Then...to really sanity check myself I looked at the behaviour of the two systems in the nearfield, in the time domain.

First the drivers.

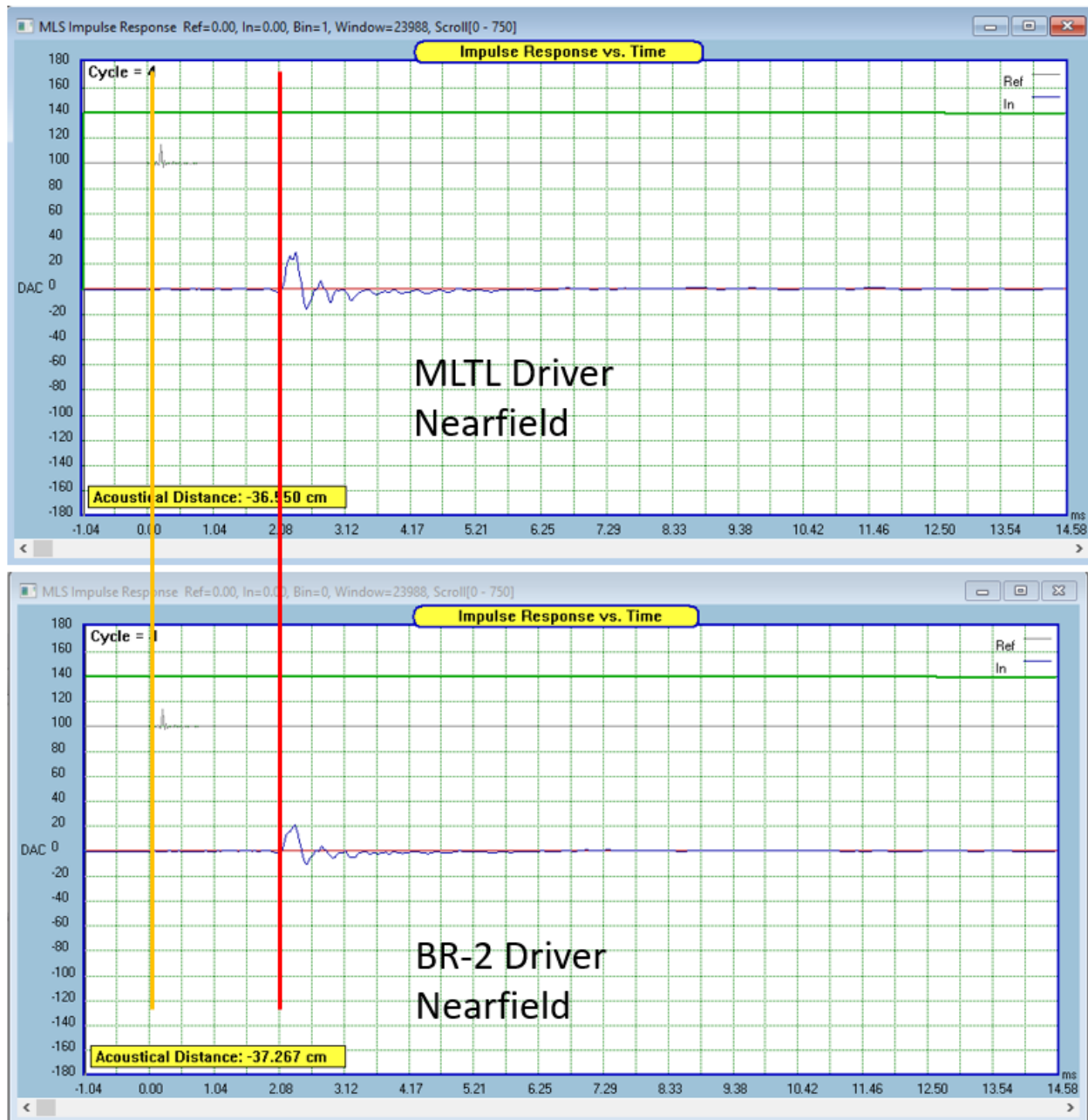


Figure 34 Nearfield Time Domain Performance.

The yellow line shows time $t=0$, where the signal was sent from the sound interface. There's roughly 2ms of latency processing the signal before it exits the amplifier, so the driver (in both the MLTL) starts responding at roughly time $t=2$ ms, shown by the second (red) line. This is what we would expect.

Next I measured both the terminus and the port at the plane of the speaker baffle.

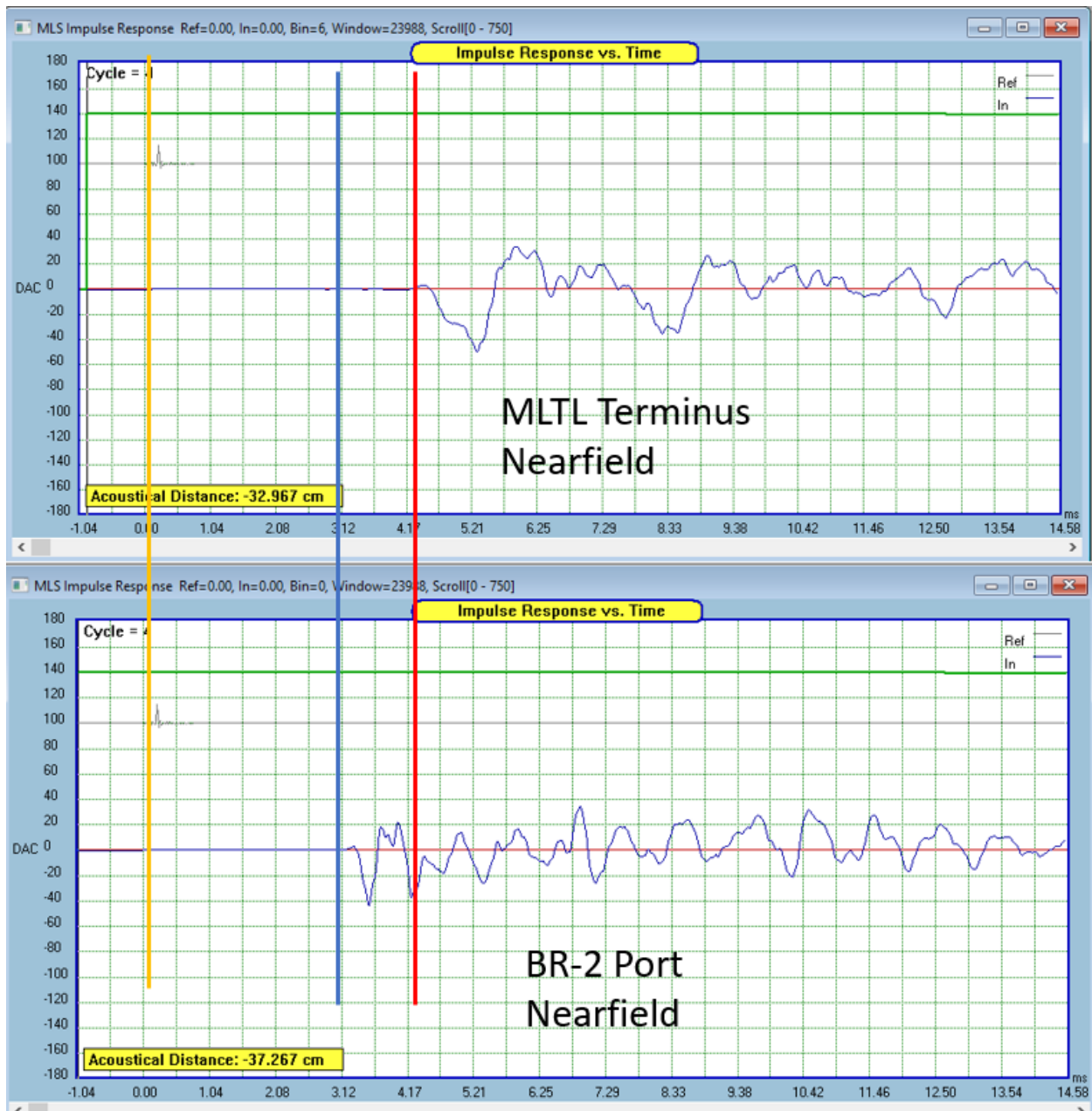


Figure 35 Nearfield Port Time Domain

The BR port starts to respond at roughly 3ms (blue line) while the MLTL terminus doesn't respond until just after 4ms (red line). Now....these are bandpass responses, and as such a difference in the bandpass response will show up as a difference in the time domain. In this case though, the overall rolloffs (until the high frequency leakage of the MLTL terminus takes over) are quite close to each other considering they are very different mechanical structures. Combine that with the system phase measurements showing the phase wraps in REW, ARTA



and SoundEasy, I suspect that the difference between the two shown in these nearfield time domain plots is real. I've said many times that fast bass isn't a thing....but the claims of improved bass time domain performance of transmission line style speakers just don't hold up to measurements for either of these designs (The SS-TL2 was similar).

Before I go any further, I'd also like to point out that these speakers were measured without stuffing. I fully expect that adding stuffing to reduce the magnitude of the line resonances could change the result. (In the case of the MLTL, it still showed it with the stuffing.) I fully expect that other structures will have different results. I can't possibly build and measure every option...but do know that for quarter-wave/transmission line/MLTL based systems the concern is real.

I would also like to point out that if your measurement routine isn't good, you won't necessarily see it. If for instance there were a bunch of room modes creeping into the measurement it will probably get swamped out. Be careful with such measurements and claims of success...it could just be a measurement error. Also, stop with the CSD plots already. They are silly for bass.

Summary, Conclusion, Musings and Other Thoughts

I had no idea the first two writeups would take off like they did. I didn't set out to spend most of my speaker time in early December doing this work. However, all of this work did clarify some thoughts I've had over the years regarding transmission lines and other designs that depend on a quarter wavelength pipe resonance for operation.

Here's the TL:DR version:

TL speakers are definitely not all they are cracked up to be.

Here's the more nuanced engineering speak version:

While the operating mode and the creation of effective models is interesting, the time domain and frequency domain performance of practical quarter wave/labyrinth/line style enclosures leaves much to be desired. There are many variables to be considered and many design choices impact more than one performance metric. As a result, it's quite difficult to get a bass alignment you want with the resonance control required for good sound, and ultimately, the performance limit is the same as a well designed bass reflex enclosure.

Really, I understand the charm. Are the things that I measured and documented for this paper going to stop me from releasing a two-way speaker with the SS-TL2 cabinet? No. Will it sound good? Yeah...I think so. If not, I wouldn't release it. Would it be far easier for me to just do a bass reflex cabinet almost 50% smaller and get equivalent, possibly better performance? Yeah.

I don't understand the concept that a TL or MLTL is equivalent to a bass reflex, I just don't. Best



case scenario, it looks like these style designs can reach the sensitivity of a bass reflex, but not exceed it. Even if that's done with a cabinet that is the same size as a bass reflex design, the inability to change the driver location or stuffing amount to deal with significantly worse resonance problems without impacting sensitivity and tuning frequency is a deal breaker for me. Clearly the underpinning physics can be modelled with the same approach, if the model doesn't handle both properly, it's a proxy and not a model of actual physical operation. However, they are not the same from a performance perspective across many different types of measurements, and they shouldn't be described as equivalent.

Most of the benefits I've seen listed for transmission line speakers don't hold up to the realities of detailed measurements. There's certainly no time domain benefits in the bass range that I can find. Prior to working on this writeup I thought they might have an advantage in output at low frequencies due to the low velocity at the terminus, and that is true for straight wall port designs. However, more advanced ports reduce or even eliminate that advantage in this testing, and the drawbacks associated with the complexities of the TL design greatly diminish their objective performance appeal. (14 year old Scott still thinks they are cool though.)