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Loudness Compensation in Automobiles

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ABSTRACT

Loudness compensation is used in audio systems to compensate for the human ear's reduced sensitivity to low-level, low frequency sounds. Volume controls in both home and automotive audio systems feature bass boost to preserve the listening experience as volume is reduced.

Equal loudness contours from ISO226: 2003 suggest that at lower listening levels, as much as 30 dB of bass boost would be needed. In a vehicle, the essentially 1/F nature of cabin noise further suggests the need for bass content elevation. But loudness functions included in most vehicular systems today lack sufficient boost to meet either equal loudness requirements or vehicle noise compensation needs.

This paper discusses the history of loudness compensation, shows samples of loudness characteristics used today and discusses a limited experiment that attempted to examine the subject's loudness compensation settings that they preferred during blind testing. These settings, and other observations of the author demonstrated an expected bass boosting and an unexpected, but similar amount of treble boosting.

Because of the ability of today's audio DSP capability and the noise present in the automobile environment, the author recommends vehicle-specific tuning at multiple sound levels from which a loudness characteristic can be derived.

INTRODUCTION AND BACKGROUND

The human hearing mechanism is less sensitive to bass at lower sound levels. This phenomenon has been documented by the derivation of equal loudness contours. These contours are made by asking subjects how the sound levels of tones compare to reference tones in apparent loudness. If, for example, a low-level tone at 1 kHz were presented along with a 40 Hz tone, the latter would have to be much higher in sound pressure level to be perceived as "just as loud".

If one presents a series of tones and then adjusts them to the same perceived loudness level, and then graphs them so as to form a line, one has a line of a single "phon" level. For example, a phon line of 40 phon intersects the 40 dB SPL level at 1kHz, then falls or rises as the tones move higher and lower.

This phenomenon has been measured in three well-known sets of experiments. First, in 1933, H. Fletcher and W. H. Munson, using headphones, gave us the Fletcher-Munson equal loudness contours (Fig. 1).[1]

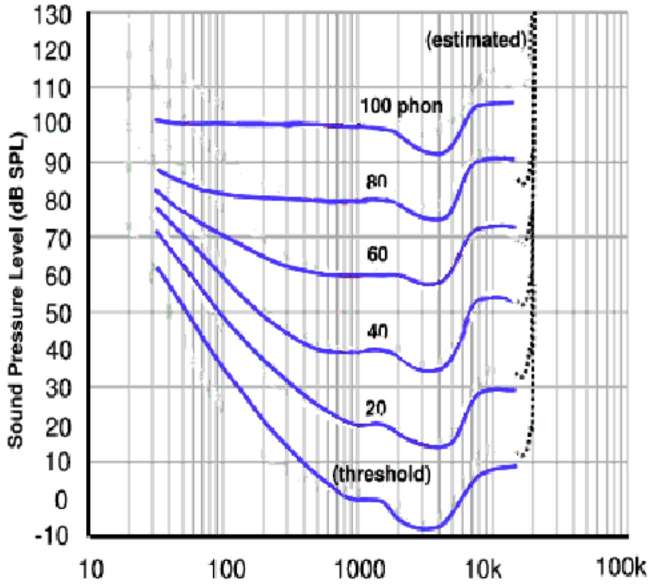


Fig 1. Fletcher-Munson Equal Loudness Contours

Later, in 1956, D.W. Robinson and R. S. Dadson performed a similar experiment, using loudspeakers.[2] Although the contours produced were similar to those of Fletcher and Munson, the amount of bass elevation was somewhat lower (Fig. 2).

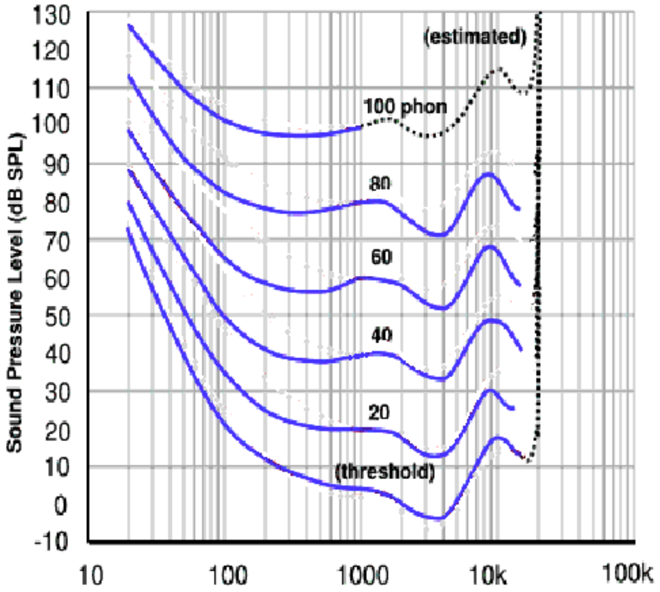


Fig 2. Robinson-Dadson Equal Loudness Contours

The Robinson-Dadson contours influenced several generations of home and automotive receivers. The ISO 226 standard accepted the Robinson-Dadson curves until 2003, when the new ISO226: 2003 set of curves was released (Fig 3).^{3} These newest curves are now widely accepted as definitive and tend to agree a bit more closely to earlier Fletcher-Munson data.

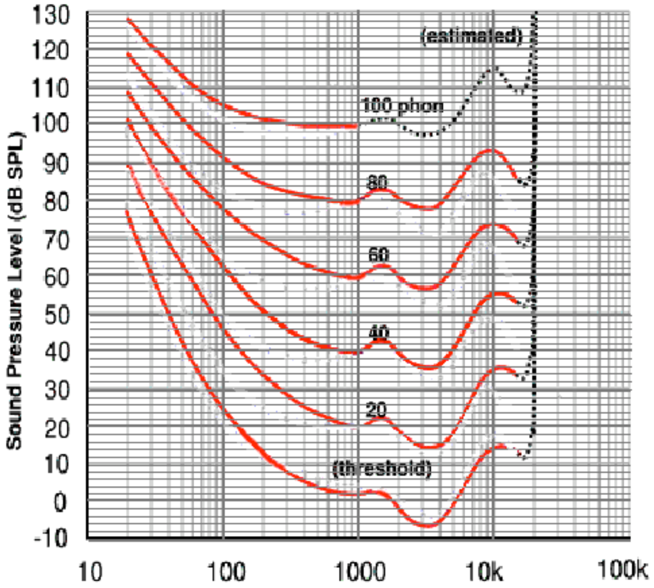


Fig 3. ISO226: 2003 Equal Loudness Contours

There are at least three more sets of equal loudness contours that are used in the noise control industry. These are based on bands of noise, and are known as NC, PNC and NR criteria.

All of these curves suggest the need for a very substantial bass lift for preservation of the listening experience at lower listening levels. But do we really need this kind of compensation?

There is a substantial school of thought that suggests every level in the dynamic range of a music performance requires its own loudness compensation. A brief analysis of this issue would suggest this thinking might not be correct:

> First, let's assume that the ISO226: 2003 curves are indicative of a continuously uniform need for additional bass as sound level is lowered. That is, the bass increase needed from 100 phon to 80 phon is similar to the bass increase from 80 phon to 60 phon, etc.
>
> If one is at a symphony concert, the softer sounds are perceived as having less bass than the louder sounds. This is appropriate and is the conductor's intent. In a good venue, the sound is as it should be, with sounds from perhaps the 100 phon level all the way down to maybe the 30 phon level. This would be a dynamic range of 70 dB. It would be hard to imagine that a conductor would amplify and equalize a soft kettledrum passage to make it "more correct".
>
> When you're listening in a home or vehicle environment, listening to 100+ phon levels could prove tiresome. For these and less critical listening situations where the primary focus is elsewhere, the conductor's 100 phon presentation is now scaled to possibly 80 phon and the entire rest of the dynamic range is lowered 20 phon as well.
>
> Now if the equal loudness concepts were somewhat applicable, the bass would sound thinner than intended. Thus some bass boosting is needed. If the system is correctly equalized at 105 phon, then the bass lift which is correct for the 80 phon line (which becomes the new "equalization reference") takes care of the production's entire dynamic range. As in a live performance, softer sounds are perceived as having less bass.

Any of these sets of equal loudness contours may or may not represent the correct amount of bass lift needed at the various phon levels on music. Perhaps for this or a number of other reasons, many different loudness compensation curves are used in the high fidelity and automotive industry today.

In motor vehicles, there is a strong masking effect caused by tire, engine and wind noise. Since the vehicle cabin noise is typically much stronger in the bass region, this noise can cover the lower octaves of music and make it inaudible. If these lower octaves are to be heard, even more bass boosting may be required than the loudness contours suggest.

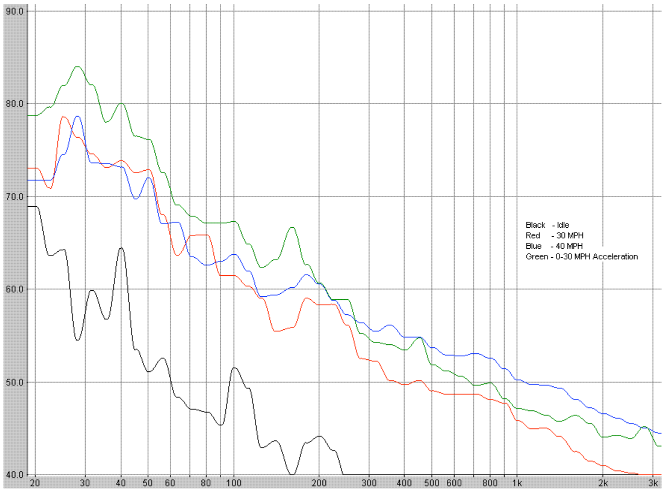


Fig 4. Automobile Noise on Highway

LOUDNESS COMPENSATION HISTORY

Designs for loudness compensation began to appear in the early days of radio. The earliest evidence the author has found for use of this compensation is in the 1935 Grunow “Tombstone” table radio receiver. This used a tapped volume control, a set up that remains in service even today (Fig 5). The basic circuit looks like this:

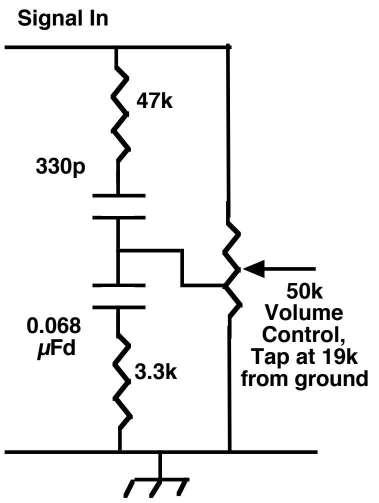


Fig 5. Tapped Volume Control Circuit

The Fig 5 circuit produces a set of volume/response curves that rather suddenly change from “flat” to “full boost” over a very small range of volume. The curves for the above circuit are shown in Fig 6.

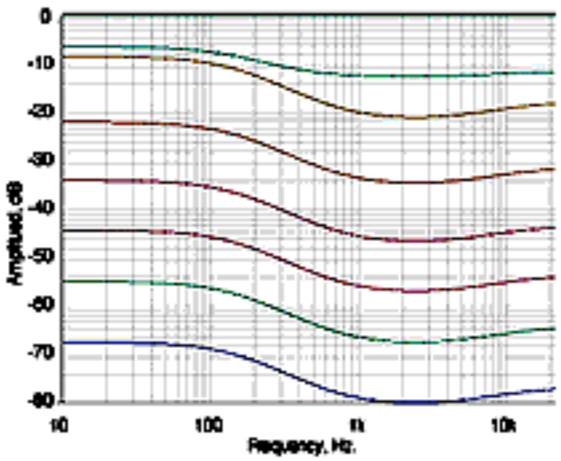


Fig. 6 Tapped Control Volume/Response Curves

While many find this setup somewhat pleasing, a personal impression is that the bass is correct at high levels, too much when the bass boost “jumps” in, then is inadequate at lower levels.

Note also that the circuit in Fig. 5. also provides a modest amount of treble boost.

Correct loudness compensation is a function of system gain; both electronic and acoustic. Perhaps that is why some early stereo receivers used both a volume and a loudness control. Instead of an in-or-out compensation, the user set gain with the volume control, and then used the loudness control to manage volume.

The tapped volume control setup was used in automotive receivers as least as early as 1955-56; the earliest evidence I have found to date is a vacuum tube Chevy radio of that vintage. In some receivers, the tone control was integrated into the loudness circuit and both tended to disappear at settings above the volume control tap.

As DSP control of volume became commonplace in automotive receivers, loudness compensation options expanded. The compensation could now be brought in more gradually, as equal loudness contours would suggest.

But again, the various implementations suggested there were many views of the correct way to provide loudness compensation. These include boosts with and without treble compensation, and bass boosts with a resonant characteristic peaking near 50 Hz.

The author decided to evaluate customer preference for bass and treble boosting with experiments. These will now be briefly discussed.

LOUDNESS COMPENSATION EXPERIMENT ATTEMPTS

> Although the experiments did not include a sufficient number of subjects from which to draw conclusions, the author is detailing elements of these experiments, which suggest the need for open thinking about loudness compensation.

OBJECTIVES

The objectives of the experiments were twofold:

1) To determine what loudness compensation a listener prefers in a quiet environment?

2) To determine the effect of automotive-style noise on compensation preference.

WHERE DOES LOUDNESS COMPENSATION BEGIN?

Right away, a problem arises in setting a level at which loudness is engaged. Where is the 100-phon line when using a piece of music that has a dynamic range of 50 dB?

This issue is managed by 1) using fixed equalization to properly adjust the listening level of the volume range used, and then 2) assuming the correct loudness compensation curve is continuous and linearly engaged as volume is adjusted.

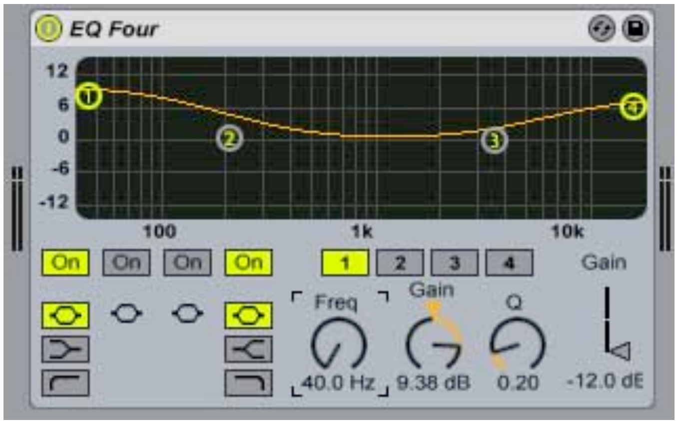
Another way of looking at this issue is that one can “hop” into the set of loudness contours at any phon level. Then, the bass and/or treble boost needed become a part of the system’s fixed equalization. The implication is of course that if the system volume is increased beyond the level at which it was equalized, the loudness compensation should actually cut bass and /or bass and treble.

When looking at the ISO226: 2003 curves, they suggest that if one had a continuously variable loudness control, one could correctly equalize a system by listening at any desired level sufficiently above the hearing threshold or noise floor.

LISTENING EXPERIMENT HOME LISTENING TESTS – FIRST ATTEMPT

The experiment’s listening test system was first set up in a home living room. A stereo speaker with subwoofer setup was used for the music information.

The bass and treble boosting was accomplished with Ableton Live computer software. The bass and treble boosts were designed to emulate rather standard tone control characteristics (Fig.7).



Freq 40.0 Hz
Gain 9.38 dB
Q 0.20
Gain -12.0 dE

Fig.7 Ableton Live Tone Curves

The simulated vehicle noise was presented via two small speakers that were under the listener’s seat and facing toward the outside right and left. The noise production setup shared the subwoofer with the music presentation system.

Several subjects were tested and while varying amounts of boosts were selected, all subjects asked for approximately the same treble boost as bass boost. The author experienced the same result as the other subjects. This result was unexpected.

This effort seemed productive, but it was abandoned, as timely support from an appropriate number of suitable listening subjects could not be found in the author’s geographical area.

LISTENING EXPERIMENT INTERNET-BASED USING SUBJECT’S COMPUTER-SECOND ATTEMPT

Using the Internet and email, a more suitable listener pool was available. This listener group was a set of volunteers from the Audio Engineering Society’s Automotive Audio Technical Committee. The methodology used clips of music recorded with various equalizations and levels that were sent to subjects.

Despite having considerable listening experience, only two of this group responded to my first, high-level “calibration” music. From the feedback I obtained, the listeners seemed to have trouble hearing 3 and 6 dB boosts of bass and treble (as did the author). This was perhaps due to a lack of stable reference and the use of pink noise to “clear” the level memory.

There may have been ways to modify the methodology, but because of time limitations and new insights about loudness compensation, efforts toward an experimental approach to loudness calibration were abandoned.

While this experiment was not concluded, it was noted that changes in bass and treble compensation were difficult for our experimenters to hear without direct A-B

comparison. This correlates with an earlier finding by David L. Clark in which level differences at the ends of the hearing range were hard to hear, even with direct ABX testing.[5]

ANALYSIS OF RESULTS FROM EXPERIMENTS

From the very limited number of subjects listening in a quiet environment, bass boosting at 12 dB of attenuation was approximately 6 dB. Every subject tested also adjusted virtually the same amount of treble boost as bass boost.

The preference for treble boost is perhaps difficult to understand. This level of boosting is unjustified by modern equal loudness contours, and other mechanisms may be operating. The possibilities include:

1. Subjects had diminished treble thresholds due to exposure to noise, ageing, etc. It was necessary to boost treble for them to hear it at all. Dr. Floyd Toole suggested this possibility.[4]

2. Subjects did not want to lower the volume, and boosting bass and treble helped them recover as much of the music as possible.

3. Subjects preferred a more balanced sound, and needed treble boost to match bass boost. This is suggested by the “rule of 400,000” (see Appendix), which suggests a preference for a balanced spectrum. [6]

Recent experience with in-car tunings by a listening class student demonstrated his preference for the same kind of treble boosting. If this preference continues to be observed, the correct loudness curve family could perhaps become similar to the ones drawn for Fig. 8.

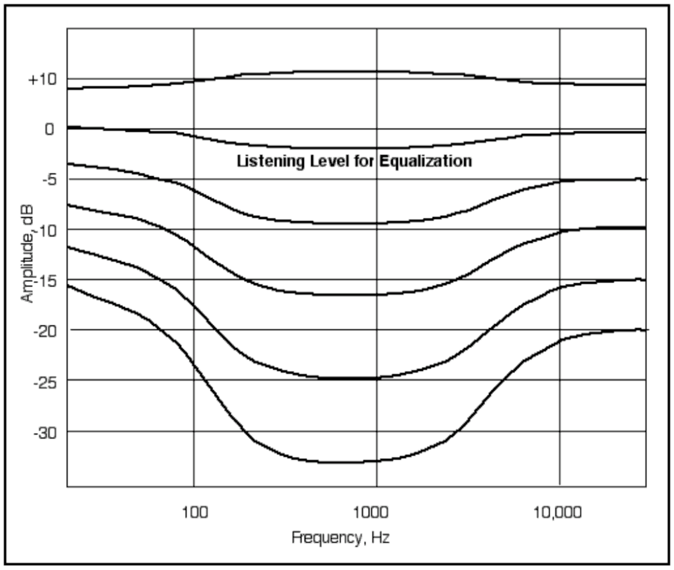


Fig. 8. Possible Loudness Compensation Curve Family

Note that in the Fig. 8 curves, the level used for tuning and measurement falls into the “loudness continuum”. Although the functions of loudness action and basic system tuning may be partitioned into different segments of code, these functions cannot be logically separated into separate areas of concern.

The author suspects that higher Q bass boosting level compensation, seen in some automotive audio systems, is used to reduce the subjective “boomy” effect of boosting higher bass-range frequencies. The “rule of 400,000”, and the author’s experience, suggests that treble boosting likewise reduces this “boomy-ness”.

INSIGHTS ABOUT LOUDNESS COMPENSATION

The author has realized that automotive designers do not need to pick a particular loudness compensation characteristic for their audio system. This is because 1) every vehicle body and trim style has at least a slightly different noise contribution, and 2) vehicle noise has a major impact on low-level listening. Thus a multi-level tuning strategy should be considered.

Today (or certainly in the recent past), some system tuners carefully adjust the audio system for their perception of a correct frequency response at a preferred listening level. The system’s receiver or DSP amplifier provides a fixed loudness compensation that determines tuning adjustments for other listening levels.

The author believes that system tuners should not be bound by the legacy of the tapped volume control. Modern DSP systems with adequate code flexibility can likely produce more suitable compensation characteristics per the system designer’s wishes.

Instead of tuning the system for one listening level and attempting to pick a suitable loudness characteristic, the author is recommending the approach of multiple volume level tunings. The system tuner would adjust the equalization for two or more listening levels and then generate a loudness characteristic that would smoothly include these equalizations.

Figure 9 provides an example of such tuning. The acoustic result of tuning at a listening level is shown as curve “A”. When the tuner adjusts the volume level to the lowest expected listening level, he tunes to curve “B”.

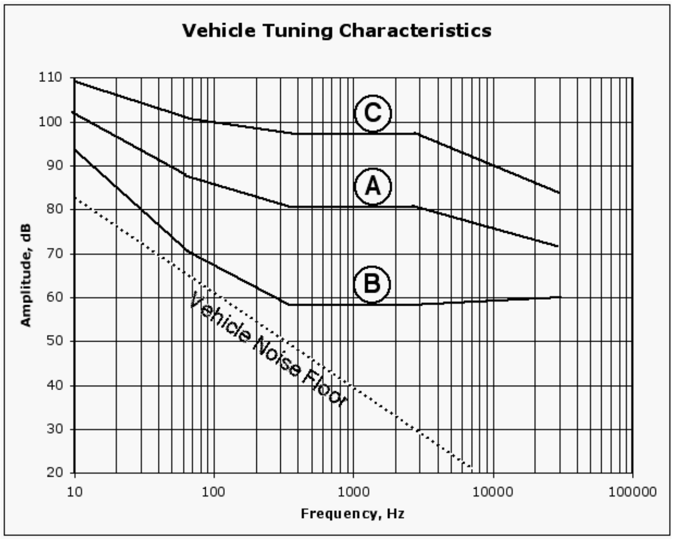


Fig. 9 Multi-level equalization

When moving from tuning “A” to tuning “B”, a complete retuning of the system would likely not be necessary. Only the general trends of bass and treble would be required, as higher Q response peaks and nulls would generally remain at the same frequency locations regardless of volume level.

Assuming that, in the example shown, the lower tuning level is sufficiently above the vehicle noise floor, loudness compensation steps could be determined by linear interpolation.

This same compensation trend could be expected to continue above the listening level and generate a high-level response something like curve “C”. Note that this would allow a fortuitous reduction of bass for the system’s woofers.

As some motor vehicles generate more low-frequency cabin noise than others, the system tuner should develop tunings at listening levels very near the noise floor to determine if loudness compensations should include a more non-linear rate of change.

The earlier experiments and in-car testing by the author indicated that treble boosting might be desirable. The system tuner should not be bound by preconceived notions about loudness compensation, but instead retune the vehicle to the most desirable tuning for each volume setting throughout the spectrum.

CONCLUSION

The author’s experience with loudness compensation suggests that few if any recently developed automotive audio systems feature loudness compensation that is optimized for customer satisfaction. Bass disappears at lower listening levels or becomes “boomy”. To the author’s ears, even with higher Q bass boosting, the treble seems dull at lower levels.

The author suggests that anyone tuning a premium vehicular audio system should not settle for a fixed loudness built into a receiver. This individual should instead include a careful, optimized family of loudness compensation responses based on a multi-level equalization strategy.

ACKNOWLEDGMENTS

The author would like to express an appreciation for the online encyclopedia Wikipedia (www.wikipedia.org), and to its contributors for their support of technical inquiry.

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4. Floyd Toole, email message to author, 13 Dec 2006

5. David L. Clark, “Some Experiments with Time”, Synergetic Audio Concepts Tech Topics, Vol. 10, Num.5 (1983).

6. Charles Nairn, Rule of "400,000 to 640,000", personal conversation with Robert Klacza, Wayne State University, Instructional Audio Department, June, 1971. See appendix.

CONTACT

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APPENDIX

Rule of 400,000: this "rule" is a general guideline for presenting a spectrum the listener perceives as balanced. The upper and lower bandwidth limits are multiplied, and that number should approximate 400,000. A full range 20-20,000 Hz sound would thus qualify.

Charles Nairn has suggest a that product range of 400,000 to 640,000 is acceptable.

If, for example, the bass were limited to 150 Hz, having a treble response to 20 kHz would sound too bright. In the first instance, 150-20,000 Hz yields a product of 3,000,000, which is greater than 640,000, and therefore too bright. In the second instance, the 20-3,000 Hz yields a product of 60,000, which is lower than 400,000, and therefore too dull.

Even though having a 20Hz lower limit is desirable, having a full 20 Hz bass response with a 3 kHz upper bandwidth limit would sound too "bassy".

This rule is not universally accepted, but the author's personal experience supports the general preference for bass-treble balance. I would further suggest that 35 Hz to 15 kHz should be considered close enough to the spectral hearing limits that further extension of either bass or treble would not likely alter the perception of spectral balance. The author looks forward to knowing the reader's thoughts on this subject.