Practical Line-Driving Current Requirements

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Introduction

Successfully driving audio lines requires good line drivers. A fact no one argues. What constitutes a good line driver, however, encourages great debate. This note examines the technical problems involved in driving audio lines, and sets down useful guidelines for successful line drivers.

Of particular concern is identifying realistic requirements. Separating relevance from truth, in line drivers. That is, while it may be *true* that one line driver's performance exceeds another; is this extra capacity *relevant* to the real world problems of driving audio lines with real audio signals? Or are you paying extra for capabilities you do not need, and cannot use?

Examining the important electrical parameters of audio lines defines the minimum specifications for line drivers. Once understood, these parameters form the basis for evaluation of different output stages.

What's Needed?

Well, first you need all the obvious things: Stable into reactive loads. Swing at least ±11 volts peak (+20 dBu). Be reliable. Run cool. Achieve the cost objectives. All these things are taken simply for granted. This is just good common sense design.

This leaves two additional, very important criteria:
- Low Output Impedance
- High Output Current

The problem comes about in quantifying these characteristics: Just how low an output impedance? And how much current? The remainder of this note sheds light on these questions.

Simplifying a Complex Problem

Let's dispel a myth right away: Practically speaking, electrical engineering transmission line theory does *not* apply to real world audio lines[1]. In spite of all the hysterical audiophile hi-fi (and lately pro audio) press to the contrary. This pseudo-science babble is nothing more than a (quite successful) disinformation campaign designed to separate a largely uninformed, and therefore, largely gullible consumer base from its discretionary income. (I've become convinced there is absolutely *nothing* audiophiles will not believe.) Madison Avenue at its worst. All under the guise of "informed experts". The only thing these people are informed experts on, is how to take your money.

Here's what they're not telling you: *transmission line effects are a function of the wavelength of the signals being transmitted.* The wavelength of audio signals is directly proportional to the speed of propagation through the medium being discussed. As an example, consider the wavelength of a 20 kHz signal. In air, with a standardized (0 °C, 0% RH) velocity of 1087 feet/sec, it is *.65 inches* (1087/20 kHz). Very short.

In wire, with a standardized velocity of about 0.7 (very conservative estimate) times the speed of light, i.e., 186,000 miles/sec x .7 = 130,200 miles/sec, it is *6.5 MILES*. Very long. And for all lower frequencies, it is even longer.

Electrically, a long line is defined as one in which the length equals or exceeds the shortest wavelength of the transmitted signal. For 20 kHz audio signals, 6.5 miles is a long line; for 1 kHz tones, 130 miles is a long line. From a transmission line viewpoint, telephone engineers deal with long lines; sound contractors do not. Don't let the wire mountebanks (look it up) tell you different. Okay, enough tutorial and editorial, back to the note.

So, transmission theory is out. This paves the way for simple R-C modeling of our audio line. Figure 1 shows an R-C circuit that models the practical audio lines encountered everyday by sound contractors. The output impedance (overwhelmingly resistive) of each leg of the output line drivers appear labeled R_{OUT}. The distributed balanced cable capacitance is lumped into one equivalent loading capacitor labeled C_{WIRE}. And the balanced input impedance (again, largely resistive) is labeled R_{LOAD}. The actual wire resistance is small enough to ignore (R_{LOAD} swamps all its effects). Similarly, for runs of 200 feet or more, the cable capacitance (normally 10-100 times greater) dominates all unit input RFI filtering capacitance.

From here, it is a small step to the equivalent half-circuit show in Figure 2. This is a conceptually easier, yet technically accurate model, analogous to examining an unbalanced line. R_O is the total balanced output resistance (twice R_{OUT}, typically 100-600 Ω). C_W is the total balanced cable capacitance (34 pF/ft for Belden 8451; other cable is as good as 20 pF/ft, or as bad as 60 pF/ft). R_L is the total balanced input resistance (typically 20k-100k Ω).
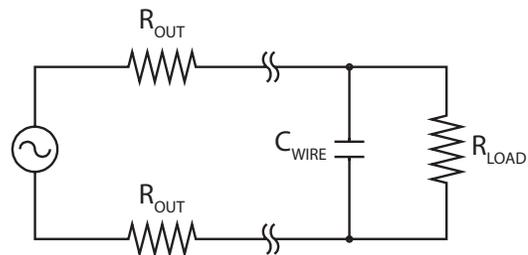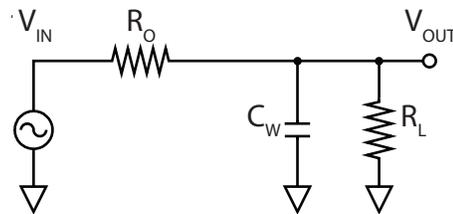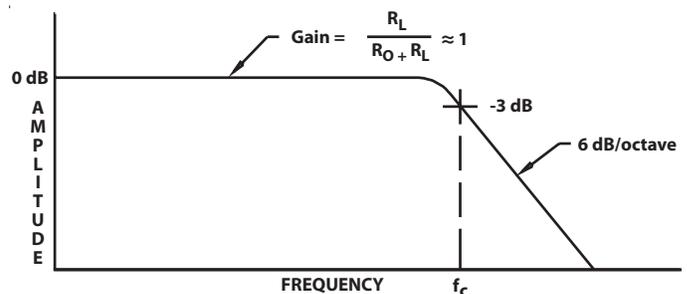

Figure 1. Simple R-C model for balanced line.

For 500 ft Belden 8451,
$C_W = (34 \text{ pF/foot})(500 \text{ feet}) = .017 \text{ μF}$

Figure 2. Equivalent half-circuit for Figure 1.

$$\text{Gain} = \frac{R_L}{R_O + R_L} \approx 1$$

$$f_C = \frac{1}{2\pi(R_L \| R_O)C_W} \gg \frac{1}{2\pi R_O C_W}$$

Figure 3. Frequency response of equivalent half-circuit.

Cable as a Low-Pass Filter

Some intuition and a little circuit knowledge helps predict the frequency response of Figure 2 (see Figure 3). At low frequencies, the impedance of the capacitor is high enough it is essentially out of the circuit. This leaves a resistive voltage divider made up of R_O and R_L. In modern designs, the output resistance is so small compared to the input resistance that this results in a neglible loss, e.g., 0.1 dB for R_O=100 Ω and R_L=10k Ω. First-order approximations treat this as 0 dB. (This example points out why you do not want to match output and input resistances. If done, you create a voltage divider of ½, since R_O=R_L. A permanent loss of 6 dB of signal — not a good idea.)

At high frequencies, the impedance of the capacitor is low enough it essentially shorts all signal to ground. This accounts for the shape shown in Figure 3 — a low-pass filter. The term, f_c, designates the corner frequency. This is defined as the frequency where the impedance of the capacitor equals the source resistance. This results in a loss of 3 dB, relative to the passband, hence, the -3 dB point. (It's not 6 dB like resistors, due to the phase angle created by the capacitor. This is phasor arithmetic.)

The exact corner frequency is given by the equivalent parallel resistance of R_O and R_L. Since R_O is much smaller than R_L, their parallel resistance essentially equals R_O. For example, the parallel result of R_O=100 Ω and R_L=10 kΩ is 99 Ω. First-order approximations treat this as R_O.

The point of all this is that *the output resistance of the line driver and the cable capacitance are critical factors in determining the bandwidth of the connected system.* Combinations of high output resistance and large cable capacitance seriously shortchange expected wide bandwidth systems. Table 1 gives the -3 dB frequency bandwidth as a function of output resistance and cable length. As can be seen, large output resistances and long cable runs do not produce wide bandwidth systems. For example, a unit with 200 Ω output resistance drives 1000 feet of Belden 8451 cable with excellent bandwidth. Yet, the same unit, changed to 600 Ω output resistance, restricts line driving to less than 500 feet for the same bandwidth. Since this is true, why do some manufacturers use larger output resistors than others? For stability reasons. Cable capacitance creates excess phase shift in the feedback networks of line drivers. Discrete output resistors buffer this capacitance and minimizes excess phase shift.

This results in more stable operation. Different manufacturer's output stage designs require different output resistors. Therefore, strictly from a designer's stability standpoint, the bigger, the better, in output resistors.

Your application dictates what you need, sometimes job by job. Knowing your cable lengths, the required frequency response (70.7 V systems, paging and AM/FM background sources, for example, cannot use 20 kHz bandwidth) and using Table 1 as a guideline, allows evaluation of the suitability of any specific output resistance for your application. In general, balanced output impedances of 200 Ω, or less, work fine for most installations.

Charging and Discharging Cable Capacitance 20,000 Times a Second

Charging and discharging cable capacitance 20,000 times a second takes a lot of current. Luckily, it's not necessary to do this to large levels. If so, hardly any line drivers would qualify.

Many articles discuss the current requirements needed to drive 600 Ω lines, which is not terribly relevant, since they are rarer than a flat loudspeaker. However, what they do not discuss and what does exist, are the current requirements necessary to drive cable capacitance. The line capacitance must be charged and discharged at a rate equal to the maximum slew rate of the system. For audio this is usually a value based upon 20 kHz. Slew rate is the maximum rate of change of voltage with respect to time. That is, you must swing so many volts in so many seconds. Analysis goes like this:

$$\text{current required: } I = C\, dv/dt$$

$$\text{where } dv/dt \text{ is maximum slew rate of system}$$

$$\text{slew rate: } dv/dt = 2\,\pi f\, V_{peak}$$

$$\text{for } f = 20 \text{ kHz: } dv/dt = (1.25 \times 10^5)(V_{peak})$$

If C is expressed in microfarads, the required current can be simplified to:

$$I = C\, V_{peak}/8$$

This is for 20 kHz signals *only*, with C given in µF.

For example, suppose you want to drive a 1000 feet of Belden 8451 to +26 dBu levels (22 V peak) with 20 kHz. How much current must the line driver deliver? Table 1 tells us that the capacitance is .034 µF, therefore:

$$I = (.034)(22/8) = 93.5 \text{ mA}$$

Table 1. Bandwidth as a function of output resistance and cable length.

CABLE LENGTH BELDEN 8451 (34 pF/ft)

Balanced Out W	500 feet (.017 μF)	1000 feet (.034 μF)	1500 feet (.051 μF)	2000 feet (.068 μF)
50	187.0 kHz	93.6 kHz	62.4 kHz	46.8 kHz
100	93.6 kHz	46.8 kHz	31.2 kHz	23.4 kHz
150	62.4 kHz	31.2 kHz	20.8 kHz	15.6 kHz
200	46.8 kHz	23.4 kHz	15.6 kHz	11.7 kHz
300	31.2 kHz	15.6 kHz	10.4 kHz	7.8 kHz
400	23.4 kHz	11.7 kHz	7.8 kHz	5.8 kHz
600	15.6 kHz	7.8 kHz	5.2 kHz	3.9 kHz

This is a *lot* of current. Very few line drivers have this capacity. If you like wasting your client's money, then insist on line drivers (for this application) that put out 100 mA.

Relevance to the Rescue

Luckily, reality tempers this problem to something manageable. While it is true you need 93.5 mA to satisfy the above example, it is also true that the example is contrived and not even close to being real. You simple do not *ever* have 20 kHz signals at +26 dBu levels. If you did, you would smoke every high-frequency driver in the house.

By examining the worst case spectral distribution of audio signals, we can predict the maximum required line driver current. This amount of current guarantees no slew limiting when driving the specified cable.

What 20 kHz levels are real? This is harder to answer than first imagined. The one thing all researchers agree on is that high frequencies are much smaller than low frequencies. Just *how much* smaller is harder to put a handle on. For music, IBM's Voss[2] claims discovery of a 1/f relationship between frequencies and level, i.e., inversely proportional — double the frequency, halve the amplitude. This says that music contains high frequencies with a natural roll-off rate of 6 dB/octave. An earlier Cabot, et al., study[3] generally supports this.

If music naturally rolls off at a 6 dB/octave rate, where does it peak? Referring again to Cabot's study, which includes review of much previous work, all data seems to peak generally in the octave around 250 Hz. If we apply the 1/f rule to these figures, then the expected response around 20 kHz would be about 38 dB less than those around 250 Hz! This seems quite extreme, but is substantiated by other studies (and agrees with IEC/DIN noise spectrum standards). Yet, other studies show that the type of music plays an important role in determining the exact peaking and rolloff rate. For example, high frequencies found within popular music tends toward larger magnitudes than classical orchestral music.

If this applies to music, does it apply to speech? Well, sort of. Like music, speech high frequency magnitudes are significantly lower than those of low frequencies. Beranek's data[4] shows the typical male speech power spectrum peaking at around 500 Hz, and dropping off at a 8 dB/octave rate above 1 kHz. This is close to music's 1/f fall, but a little steeper and peaking about an octave later. Female speech tends to peak another octave higher, with a similar rolloff rate.

Some generalities are possible. What's needed is an ultra-conservative this-will-never-get-you-into-trouble guideline. Here is mine: *To calculate current (**only**), I figure real audio signals (speech or music) stay flat out to 5 kHz and then rolloff at a 6 dB/octave rate.*

Understand this takes the worst case studies, and then builds in at least another two-to-one safety margin. Very conservative, but it correctly models the shape of real music and speech signals. And it is not nearly as conservative as assuming a flat 20 kHz spectra. That is totally unfounded. Remember *this is only for current calculations.* Line driver *voltage* response must remain absolutely flat to 20 kHz.

Calculating maximum current availability based on the above premise guarantees no slew limiting when driving cable. If this *ever* gets you into trouble, do two things:

- Replace all your fried high-frequency drivers.
- Call me, and I'll bring the beer and we'll discuss which is more audible, slew limiting or blown drivers!

Calculating Maximum Current Demands

My rule of "flat to 5 kHz with a 6 dB/octave rolloff thereafter" makes for simple current calculations. Since 20 kHz is two octaves away, the amplitude will be 12 dB less, which is a factor of four. And 20 kHz is four times 5 kHz. So they cancel. That is, the frequency is four times greater, but the amplitude is four times less, so they cancel. This means we can calculate our current requirements using:

- A frequency of 5 kHz.
- The expected maximum signal level.
- The total cable capacitance.

Let's go back to our original example. Now we use 5 kHz instead of 20 kHz. Since slew rate is directly proportional to frequency, and current is directly proportional to slew rate, our new formula is simply ¼ of our old one:

$$I = C\ V_{peak}/32$$

Since we are being conservative, we can fill-in a worst case value of +26 dBu for V_{peak}. This yields a simplified formula for *peak* current as follows:

$$I = 0.7\ C \text{ (where C is in μF)}$$

So, for our example with .034 μF (1000 feet of Belden 8451), we need:

$$I = (0.7)(.034) = 23.8 \text{ mA peak (16.8 mA rms)}$$

Or, approximately ¼ what we previously calculated. Moral of the story: *Don't pay for what you don't need.*

If the load impedance is less than about 10k Ω, you must include extra current for driving the resistance. So if the load impedance really is 600 Ω (for mystical, strange and unknown reasons), add the following for +26 dBu levels:

$$22\ V_{peak}/600 = 36.7 \text{ mA peak (25.9 mA rms)}$$

But we cannot simple add them (life is never simple, you know that). Due to the phase relationship between resistors and capacitors, currents through them do not add like normal numbers. Instead they add by taking the square root of the sum of the squares (phasor arithmetic), i.e.,

$$(25.9 \text{ mA}^2 + 16.8 \text{ mA}^2)^{1/2} = 30.9 \text{ mA rms}$$

Therefore, our example of driving 1000 feet of cable, terminated in 600 Ω, to +26 dBu levels, requires approximately 31 mA from the output devices.

Okay, but how do you tell whether any particular device has that much current? Check the data sheet, ask the manufacturer, or consult the schematic and see if the output ICs show up in Table 2. In general, Rane products use 5534s and SSM2142s as output line drivers. Check the individual schematics, or contact the factory for the exact devices used in any specific product.

Table 2. Current ratings of popular ICs used as output line drivers.
(Vs=±15 VDC; TA=25°C; all data typical instantaneous values)

IC	RMS CURRENT	PEAK CURRENT	MANUFACTURER
AD845	35 mA	50 mA	Analog Devices
HA4741	11 mA	15 mA	Harris
HA5221	40 mA	56 mA	Harris
LM627	24 mA	33 mA	National Semiconductor
LM6321*	212 mA	300 mA	National Semiconductor
LT1028	28 mA	40 mA	Linear Technology
LT1115	28 mA	40 mA	Linear Technology
NE5532	27 mA	38 mA	Philips / Signetics
NE5534	27 mA	38 mA	Philips / Signetics
	42 mA	60 mA	Analog Devices/PMI
	42 mA	60 mA	Analog Devices/PMI
TL074	12 mA	17 mA	Texas Instruments
TLE2027	25 mA	35 mA	Texas Instruments

*High speed buffer; requires op amp.

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