What's All This Critical Length Stuff, Anyhow?

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Bob Pease writes a regular column for Electronic Design magazine. The title is very often "What's All This (---) Stuff, Anyhow?" With apologies to Mr. Pease, I just couldn't resist starting this particular column the same way!

The critical length of a PCB trace is an issue that mystifies and confuses many designers. Most of us are aware that traces can, under some circumstances, begin to look like transmission lines, and that transmission lines can cause signal reflections that can cause signal integrity problems. Most of us are aware that this can be a problem with "long" lines, but probably not with "short" lines. And most of us are aware that the "critical length" may be some magical point that divides "long" from "short".

The rules we hear sometimes seem to be without basis, or sometimes even confusing. One person might simply say the critical length is 3" for a one-nanosecond rise time. Another might say the critical length is where "the two way delay of the signal equals the rise time."

And some of us wonder why there is a critical length at all!

To start this discussion I am going to ask you to do two things. The first is to stop thinking about critical length as a distance (e.g. inches) and start thinking about it as "time." The second is to think about this whole issue in terms of a general communications model (**Figure 1**).

A general communications model consists of a sender, a message, a receiver, and a medium over which the message is sent. On a circuit board, this would seem to be straightforward. The sender is a switching device, the receiver is the receiving device, the (digital) message is (usually) the transition from one state to the other that occurs during the rise (or fall) time, and the medium is the trace. But, we could also consider the receiver to be an FCC compliance testing antenna, and we might not be sure at all about any of the other three! In a general sense, the sender could be a person speaking in a room, the receiver could be someone in the room, the message is the words he is speaking, and the medium is the air and space that separates them. If the speaker uses a microphone, the medium is a little more complicated. And, if the sender and receiver are communicating over the phone, the medium could be a confusing mix of wires, microwaves, satellites, etc.

Sender < **Message Media** > **Receiver**

Figure 1
Elements of a general communications model

If there is a communication problem, there are at least four ways it might be helped. (1) Send (transmit) the message more clearly. (2) Improve or simplify the message (slow it down, encode it, use error detection, etc.) (3) Use a more sensitive or discriminating receiver. Or, (4) improve the medium over which the message travels. Each of these is a reasonable and legitimate way to improve communications.

Here is a relatively common kind of communication problem. Say you are (the receiver) in a stadium. There is an announcer (sender) who transmits (his message) through a speaker system. It takes time for the message to get from the speakers to you. The sound also reflects off other surfaces in the stadium so you hear echoes. In some situations, the echoes are so bad you can't understand the message. Therefore, there is a communication failure!

To correct for this failure, as the receiver, you can listen harder. You can move closer to the speaker, so that the message is clearer and you receive it before you hear the echoes. The announcer can simplify the message or slow it down (speak more slowly). Or the stadium could be acoustically engineered to prevent, absorb, or attenuate the echoes.

Now, think of a message moving down a trace in terms similar to the announcer in the stadium. The message flowing down the trace (medium) reflects off the end of the trace just as sound echoes off a hard surface. **Figure 2** illustrates a situation where the medium is "engineered" to absorb the reflections, so there are no "echoes." In **Figure 3**, however, there is no engineering and significant reflections (echoes) are occurring off several surfaces (both ends of the trace.) Clearly, the message is easier to understand when the medium has been properly engineered.

What can be done to improve the situation illustrated in Figure 3? One thing to do is properly engineer the medium to prevent reflections (echoes). In a stadium we might use sound absorbing materials. On a trace, we might properly "terminate" it with a resistor carefully chosen to absorb the reflections. Or, we could move the receiver closer to the sender (shorten the trace) or slow down the message (reduce the rise and fall times).

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These latter two solutions have the same effect. Either one results in the receiver receiving the message more quickly before other noise sources interfere. How close is close? Well if the receiver is close enough to receive the message *as it is being sent*, there is a good chance of receiving it clearly. If the message takes a nanosecond to send, that means being *less* than a nanosecond away. On the other hand, if it takes a nanosecond to send the message, and the receiver is three or four nanoseconds away (analogous to the stadium illustration), and if the medium (trace) has not been properly engineered, *then* reflections (echoes) might well interfere with and obscure the message.

So, if you are close enough to be receiving the message as it is being sent, and well before it is completed, you are probably close enough to understand it regardless of the medium. If the message takes a nanosecond to send, that means you are significantly closer than a nanosecond to the sender. Since signals travel approximately six inches in a nanosecond on a PCB (made from FR4), if you are closer than about three inches away, you are starting to receive the message before it is half completed.

That's why people tend to say the critical length is about 3 inches for a one-nanosecond signal!

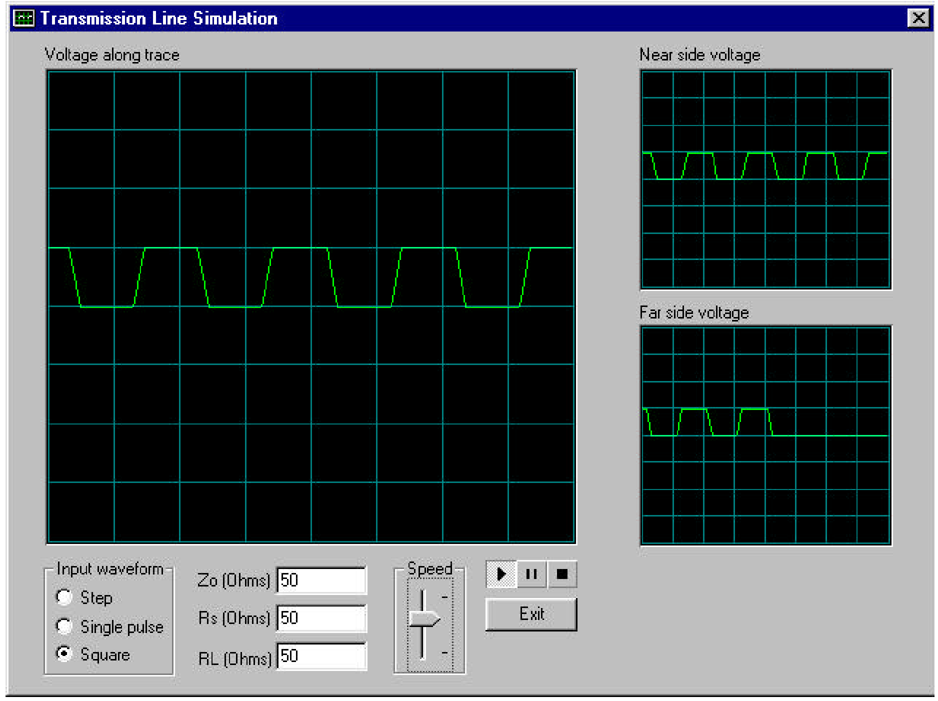

Figure 2
With proper engineering, reflections do not occur and the message is clear no matter how far away the receiver is.

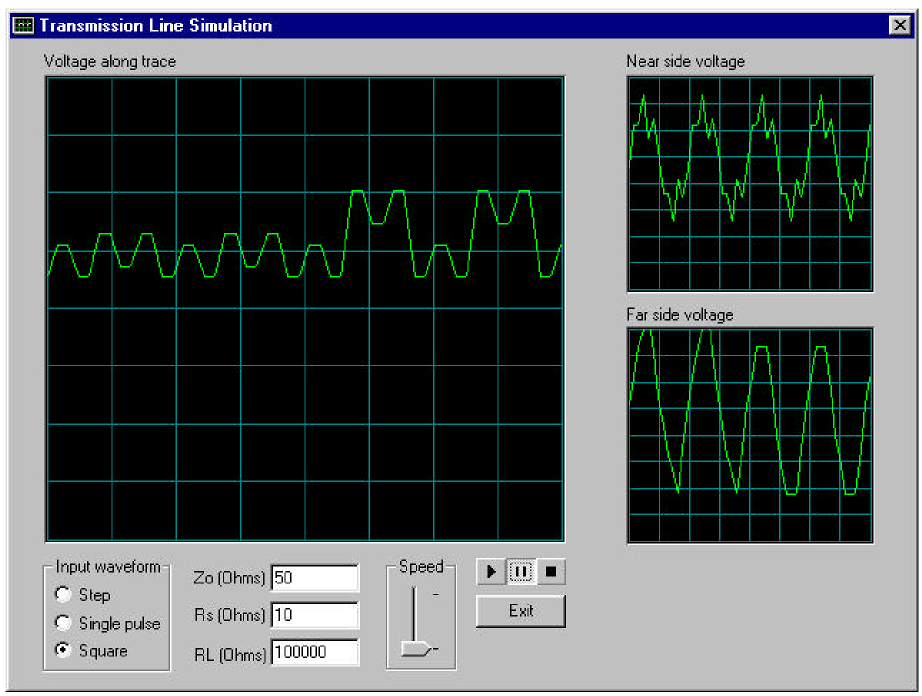

Figure 3
Without proper engineering, reflections can seriously distort the message for receivers that are too far away