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Determination of a Sound Level for Railroad Horn Regulatory Compliance

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1.0 INTRODUCTION

The Federal Railroad Administration (FRA) has undertaken a rulemaking process to address the use of locomotive horns at public highway-railroad grade crossings [1]. This rule includes a provision to regulate the sound level output of railroad horns. This letter report supports the rulemaking by describing the process used to determine a railroad horn output sound level required for motorist detection. This sound level is defined as the sound level at which there is a 95% likelihood that a person with normal hearing will hear (detect) an average train horn at the instant in time at which detection must occur to avoid a collision. Generally, detection is based on the relative strength of the signal in the motorist's ambient noise environment.
The sound level is tied to an estimate of an average maximum motor vehicle speed and an average maximum locomotive speed. Locomotive horn sound level data measured by the Volpe Center Acoustics Facility at the Transportation Test Center (TTC) in April 2001[2], along with automotive insertion loss and interior noise data measured and documented by the Volpe Center in earlier research [3] provide the basis for the determination of the likelihood of motorist detection.

Section 2 summarizes the elements of the signal-to-noise analysis, which provide the basis for the determination of the detectability of the signal. Section 3 summarizes the elements of signal detection theory used to calculate detectability and a corresponding probability or likelihood that the motorist will detect the horn. Section 4 presents an example calculation. Appendix A presents background on signal detection theory.

2.0 ELEMENTS OF SIGNAL-TO-NOISE ANALYSIS

This section summarizes the elements used in the signal-to-noise analysis. These elements are presented in a source-path-receiver format commonly used in the analysis of transportation noise. In this analysis, the source of the acoustic signal, the railroad horn, creates a sound, which propagates along a path to the motorist, or receiver. Section 2.1 discusses the source of the data used to represent the railroad horn signal. Section 2.2 discusses the propagation to the motorist at that instant detection must occur to avoid a collision. Section 2.3 discusses the motorist's ambient noise environment.

2.1 SOURCE: THE RAILROAD HORN SIGNAL

Locomotive horn sound levels measured by Volpe Center Acoustics Facility staff at the Transportation Test Center (TTC) in Pueblo, CO, during April 2001 provide the necessary data to determine relative strength of the railroad horn signal. Sound level output and directivity data were measured for four models of locomotive horn, (K-5-LA, K-5-LAR24, RS-3L, and RS-3L-RF) installed in two locations (Cab-Roof and Center) on a GP-40 locomotive. Data also exist for the K-5-LA installed on the cab roof of a SD60-MAC locomotive.

The development of sound levels for national use described in this report are based upon data from the measurement of specific horn types and installation locations, combined to represent an 'average horn'. The 'average horn' used in this analysis was developed using information on the relative distribution within the United States of each type of horn in each installation location. Horn types were classified into general types using the directionality of the chimes (directional – all forward facing, and bi-directional – forward and rearward facing), and the number of chimes (three or five). The relative distribution of each type of locomotive horn and their installation locations in the U.S. was assembled from an informal poll of Class I* railroads which was conducted as a part of the development of the Draft Environmental Impact Statement of the Proposed Rule. One of the poll questions asked railroads to estimate the make/model and installation location of the railroad horn on each in-service locomotive. Two railroads responded to these queries, representing 23.5% of the US locomotive fleet at that time. There is no reason to believe this is not representative of the railroad industry because these railroads were large and geographically diverse. From this, the approximate distribution of directional and bi-directional three-chime and five-chime horns in the US was determined, as summarized in Table 1. Unfortunately, however, these railroads were not able to provide information on the installation location of each type of horn. Beginning at least a decade ago an increasing percentage of new locomotives were provided with center-installed bi-directional horns; this type is now the predominant configuration for new locomotives. Recent economic downturn may have raised the proportion of center-installed horns even higher. Due to these uncertainties, it was assumed that half of the locomotive fleet consists of cab-roof installed horns and half the locomotive fleet consists of center-installed horns. Table 1 also shows the specific horn used to represent each horn type.

Table 1. Approximate Distribution of Horn Types Within the US

Horn Type	**Installation Location**	**Percentage of Fleet**	**Data Source** (Horn Model/ Engine)
Directional 5-Chime	Cab Roof	2.66%	K-5-LA / GP40 & K5-LA / SD60-MAC
	Center	2.66%	
Bi-Directional 5-Chime	Cab Roof	20.00%	K-5-LAR24 / GP-40
	Center	20.00%	
Directional 3-Chime	Cab Roof	6.00%	RS-3L / GP-40
	Center	6.00%	
Bi-Directional 3-Chime	Cab Roof	21.33%	RS-3L-RF / GP-40
	Center	21.33%	

2.2 PROPAGATION PATH

The signal from the railroad horn must first propagate over a distance before reaching the motorist. Because the locomotive and the motorist are both in motion, this distance changes as a function of time and speed. There is a temporal threshold where detection of the signal from the railroad horn is critical; this is the instant at which the motorist must react and engage the vehicle's brakes to stop before reaching the crossing in order to avoid a collision, termed the critical time and denoted T_{cr}. The propagation path distance between the locomotive horn and

* A freight railroad with an annual gross operating revenue in excess of $250 million (based on 1991 dollars) is designated Class I.

the motorist at this moment in time are a function of both locomotive speed and motor vehicle speed. Section 2.2.1 discusses the calculation of the critical time and the grade crossing geometry at this time. Section 2.2.2 discusses the elements of signal propagation.

2.2.1 Critical Grade Crossing Geometry

As stated above, the critical time is the instant at which the motorist must react and engage the vehicle's brakes to stop before reaching the crossing in order to avoid a collision. It is a function of driver reaction time (assumed to be 2.5 seconds), the minimum motor vehicle stopping distance, critical track zone, and motor vehicle length. Reference [4] provides a detailed description of this calculation.

Once T_{cr} is calculated, the propagation path distance and angle between the railroad horn and the motorist can be determined. This distance is referred to as the minimum warning distance, defined as the distance between the motor vehicle and the front of the locomotive at T_{cr}. Also of importance is the sound emission angle; the locomotive horn's sound output is greatest to the front of the horn and generally decreases to the sides and rear of the horn. Figure 1 illustrates the grade crossing geometry at T_{cr}.

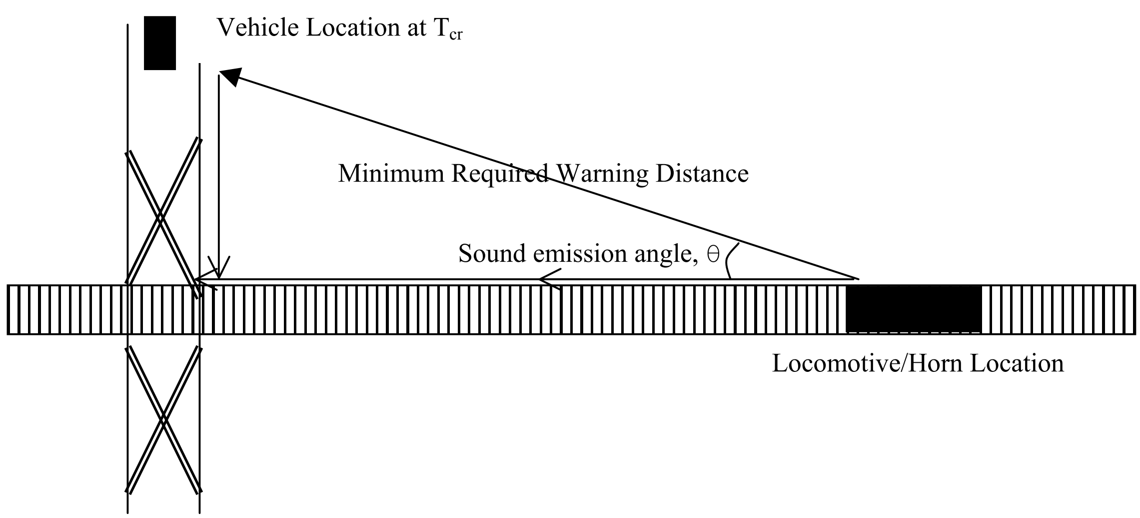

Figure 1. Critical Grade Crossing Geometry

2.2.2 Acoustic Propagation

Based on the distance between the source (horn) and the receiver (motorist), the sound level of the warning signal is adjusted for propagation losses. This is accomplished using the measured locomotive horn sound level data, consisting of one-third octave-band sound levels measured at a distance of 200 ft from the horn, 0 degrees from centerline, and overall sound levels measured at a distance of 200 ft, 0 and 45 degrees from centerline. The sound level data measured for each horn at a distance of 200 ft, 0, 45 and 90 degrees from centerline, was linearly interpolated to determine the sound level at the sound emission angle, θ. The difference between this sound level and the sound level at 0 degrees was applied to each one-third octave-band sound level measured at 200 ft, 0 degrees; in this manner the one-third octave-band data was adjusted to be representative of 200 ft, Θ degrees from centerline. The one-third octave-band data is then adjusted for spherical spreading, atmospheric absorption, and excess ground attenuation over the distance between the horn and the motorist. In an analysis based on a sound level at a particular instant in time, propagation assumes point source or spherical spreading (6 dB per distance doubling). Atmospheric absorption was calculated based on SAE ARP-866A under conditions of 77°F and 70% relative humidity. Excess ground attenuation was assumed to be zero based on empirical data which show that there is no excess ground attenuation for horns at a height of 16 ft above ground level.

The signal at the motorist's location was further adjusted using motor vehicle insertion loss data measured by the Volpe Center. In this manner, the data is then representative of signal levels *inside* the motor vehicle. Motor vehicle insertion loss data represent an average of seven 1990-1992-model year automobiles. While current vehicle models may differ from this pool of automobiles, this data is the best available. No data were available for the insertion loss of other types of vehicles, such as trucks and buses.

2.3 AMBIENT NOISE

The ambient noise inside a motor vehicle is generally dominated by noise resulting from motor vehicle operation. The motor vehicle interior noise level data, measured by the Volpe Center, were used as the basis for calculation of detection likelihood. These data represent an average of seven vehicles operating at 30 mph with no interior ventilation systems or radio in use. Although it would be desirable for the interior noise to be representative of conditions at higher speeds, there have been no recent applicable measurements. A higher speed will generally result in higher interior noise levels, requiring a louder signal for detection. Measurements of late 1970's model vehicles[5] show that the interior noise may increase 4 to 16 dB between 30 and 55 mph. It is not known if these relative differences are applicable to the 1990's model year vehicles.

3.0 SIGNAL DETECTION THEORY

The probability (or likelihood) of hearing a horn can be determined from the relative values of signal and noise using signal detection theory (SDT). This probability is determined by calculating a value called the detectability index, termed d' (d prime). For auditory detection, d' is defined as the band-width-adjusted, signal-to-noise ratio (S/N). Appendix A presents a detailed discussion of this theory.

$$d'_{band} = \frac{\eta S(\omega)^{.5}}{N} \qquad (1)$$

Where η= the efficiency of the observer at a particular frequency
ω =1/3 octave bandwidth
S = the signal level in terms of sound pressure re: 20 microPascals, and
N = the noise level in terms of sound pressure re: 20 microPascals.

The above equation is used to calculate d' in each one-third octave band from 160 Hz to 10 kHz. The overall d' or d'_{total} is calculated as the vector sum of $d'_{band.}$

$$d'_{total} = \sqrt{\sum d'_{band}{}^{2}} \qquad (2)$$

As discussed in Appendix A, the theoretical value of d' necessary for a 95% likelihood of detection for an 'ideal observer' is calculated to be 4.31. This value conservatively assumes that the observer has only a 10% expectation of encountering a train. After adjustments are made for the difference between an ideal observer and a human observer, as discussed below, this value can be used with Equations 2 and 3 to determine the required signal level.

3.1 DETERMINATION OF A REQUIRED SIGNAL LEVEL

If the 'ideal observer' were to approach a grade crossing and encounter a signal with a d'=4.31 and p(train) = 0.1, there would be a 95% likelihood of detection. Unfortunately, human beings cannot detect sound as an ideal observer. Rather, there is some value of d' at which the signal becomes audible to a human observer. This value is referred to as audibility, denoted a'. Research funded by the National Park Service (NPS) [6,7] has empirically determined that, in outdoor recreational settings, an aircraft is audible when its d'=5. This value is referred to as audibility, denoted a', where a'=d'/5.

This research further defines another quantity, noticeability. It states "Noticeability of a signal expresses the degree to which an observer who is engaged in an activity other than actively listening for acoustic events will notice an (otherwise audible) signal. In an outdoor recreational setting, an aircraft over flight is noticeable at a value of d'=50. Noticeability may be expressed an n', where n'=d'/50." In other words, anything with a d'>50 is 'noticeable'.

There has been no research to date testing the applicability of these threshold values for audibility and noticeability to train horn detection by a motorist. In the absence of this research, noticeability should provide a conservative basis for the determination of the likelihood of detection of a train horn. In addition, when a motorist is approaching a passive crossing, he/she may not be actively listening for the signal, a situation akin to the definition of noticeability. Therefore, a signal with an n' = d'/50 = 4.31 is defined as having a 95% likelihood of detection for a motorist approaching a crossing.

To determine the sound level at which the signal from a horn will the approach the desired level of n'=4.31, it is easiest to convert the noticeability index to a noticeability level, denoted n'L.

$$n'L = 10\log n' \qquad (3)$$

Using Equation 4, the measured noticeability level ($n'L_{measured}$) is calculated and compared to the noticeability level criteria ($n'L_{criteria}$), calculated as 10log(4.31) = 6.3 dB. The difference between $n'L_{measured}$ and $n'L_{criteria}$ is equal to the difference between the measured horn output ($L_{eq\ measured}$) and the horn output that will meet the detectability criteria ($L_{eq\ criteria}$).

$$n'L_{measured} - n'L_{criteria} = L_{eq\ measured} - L_{eq\ criteria} \qquad (4)$$

For example, the sound output of a horn was measured at the compliance measurement location, 100 ft forward of the locomotive, as $L_{eq\ measured}$ = 114 dB(A), the corresponding $n'L_{measured}$ was calculated to be 16.3 dB. From Equation 4, 16.3 - 6.3 = 114 - $L_{eq\ criteria}$, therefore $L_{eq\ criteria}$ = 104 dB. Thus, the output of this horn could be reduced by 10 dB so that it measures 104 dB at the compliance measurement location.

4.0 EXAMPLE CALCULATION

In order to apply the theory of signal detection, described in Section 3, to determine a single reasonable railroad horn output level, a conservative estimate of the average maximum for both the speed of the motor vehicle and the speed of the locomotive at railroad crossings in the U.S. was derived from available databases.

The average speed of the locomotive was assumed to be the per train average of the maximum time-table speed (i.e., maximum allowable speed) through each qualified grade crossing in the FRA inventory[8]. Qualified grade crossings were defined as public at-grade crossings with train count values.

$$\text{Average Locomotive Speed} = \frac{\sum_{i=1}^{130666} \text{Total Trains at Crossing i} * \text{Maximum Time Table Speed at Crossing i}}{\text{Total Trains}}$$

Where i = Grade Crossing number

For the 130666 crossings with train count data in the FRA inventory, the average maximum timetable speed is 48.5 mph.

The average speed of the motor vehicle was calculated using data from the Fatality Analysis Reporting System maintained by the National Highway Traffic Safety Administration [9]. For each fatal highway-railroad grade crossing collision, the posted speed limit on the roadway was extracted from the database. For the years 1996-2000, there were 1343 collisions where the posted speed was reported. The average of these speeds is 41 mph.

Using the methodology outlined by Aurelius and Korobow, T_{cr}, minimum warning distance, and sound emission angle were calculated for a grade-crossing scenario where a motor vehicle is traveling at 41 mph and a locomotive is traveling at 48.5 mph. A motor vehicle traveling 41 mph will need 172.2 feet (52.5 m) in order to stop, and will take 3.7 seconds to do so. Assuming that the average driver reaction time of 2.5 seconds, the motorist will therefore need to detect the horn 6.2 seconds before reaching the crossing in order to react to the horn, engage the brake, and bring the motor vehicle to a stop. This occurs when the motor vehicle is at a distance of 371.7 ft (113.3 m) from the crossing. At this same point in time (6.2 seconds before reaching the crossing), a locomotive approaching at 48.5 mph will be at a distance of 439.6 ft (134.0 m) from the crossing. The resulting distance between the two (minimum warning distance) is 575.8 ft (175.5 m). The sound emission angle is 40.2 degrees.

The following section will show how the optimal sound level for a 95% likelihood of detection was determined in the aforementioned scenario for the K-5-LA installed on the cab roof of a GP-40 locomotive.

Table 2 shows the overall L_{eq} measured under the constant pressure test conditions (135 psi) 200 ft from the horn at 0, 45, and 90 degrees from the centerline of the locomotive, and the Leq at the critical emission angle of 40.2 degrees, interpolated from measurements at 0 and 45 degrees.

Table 2. Overall Measured Sound Level

Angle (deg)	Measured L_{eq} at 200 ft (dB(A))	Interpolated L_{eq} at 200 ft (dB(A))
0	107.0	
40.2		104.9
45	104.7	
90	99.7	

In other words, at 200 ft, the sound level at an emission angle of 40.2 degrees is 2.1 dB(A) lower than the sound level at 0 degrees. Using this information, each one-third octave-band[†] sound level measured at 0 degrees, 200 ft, was adjusted by –2.1 dB(A) to be representative of one-third octave-band sound levels at 40.2 degrees, 200 ft, summarized in Table 3.

Table 3. Sound Level Data Interpolated to 40.2 degrees

	One-Third Octave-Band Center Frequency (Hz)																		
	160	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10K**
SPL (dB) at 0 deg, 200 ft	50.8	59.1	61.4	90.5	99.2	99.1	98.3	101.8	96.2	96.2	95.5	95.8	92.8	93.7	91.1	88.7	84.1	81.1	76.0
SPL (dB) at 40.2 deg, 200 ft	48.7	57.0	59.3	88.4	97.1	97.0	96.2	99.7	94.1	94.1	93.4	93.7	90.7	91.6	89.0	86.6	82.0	79.0	73.9

The one-third octave band data at 200 ft, 40.2 degrees are propagated to the motorist's location at the critical time, 575.8 ft from the horn. Propagation assumes spherical spreading (6 dB/distance doubling) and atmospheric absorption at 77 ° F and 70% relative humidity.

Table 4. Sound Level Data Propagated to 575.8 feet

	One-Third Octave-Band Center Frequency (Hz)																		
	160	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10K**
SPL (dB) at 40.2 deg, 200 ft	48.7	57.0	59.3	88.4	97.1	97.0	96.2	99.7	94.1	94.1	93.4	93.7	90.7	91.6	89.0	86.6	82.0	79.0	73.9
Spherical Spreading	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2	-9.2
Atmospheric Absorption	-0.11	-0.13	-0.17	-0.21	-0.26	-0.33	-0.42	-0.53	-0.67	-0.84	-1.08	-1.37	-1.73	-2.21	-2.87	-3.26	-4.16	-5.59	-7.75
SPL (dB) at 40.2 deg, 575.8 ft	39.4	47.7	50.0	79.0	87.7	87.5	86.6	90.0	84.3	84.1	83.1	83.2	79.8	80.2	77.0	74.2	68.7	64.2	57.0

The one-third octave band data is then adjusted to account for motor vehicle insertion loss.

[†] Because the lowest fundamental frequency of any of the horns is 255 Hz, data below 160 Hz were not included in the analysis.

Table 5. Sound Level Data Inside the Motor Vehicle

	One-Third Octave-Band Center Frequency (Hz)																		
	160	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10K**
SPL (dB) at 40.2 deg, 575.8 ft	39.4	47.7	50.0	79.0	87.7	87.5	86.6	90.0	84.3	84.1	83.1	83.2	79.8	80.2	77.0	74.2	68.7	64.2	57.0
Insertion Loss	-12.1	-14.6	-14.3	-15.4	-20.5	-24.4	-28.2	-29.3	-28.5	-29.9	-33.8	-32.1	-33.7	-34.0	-34.0	-34.9	-38.3	-42.6	-43.8
SPL (dB) inside motor vehicle	27.3	33.1	35.7	63.6	67.2	63.1	58.4	60.7	55.8	54.2	49.3	51.1	46.1	46.2	43.0	39.3	30.4	21.6	13..2

The SPL inside the motor vehicle and the interior noise inside the motor vehicle are used in Equation 1 to calculate d' for each one-third octave band. The d'_{total} is calculated as the vector sum of the individual $d'_{band.}$ Note that the Signal and Noise must first be converted to sound pressure from sound pressure level (SPL) (sound pressure = $10^{(SPL/10)}$).

Table 6. Summary of d' Calculation

	One-Third Octave-Band Center Frequency (Hz)																		
	160	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10K**
Signal (SPL)	27.3	33.1	35.7	63.6	67.2	63.1	58.4	60.7	55.8	54.2	49.3	51.1	46.1	46.2	43.0	39.3	30.4	21.6	13..2
Noise (SPL)	55.1	54.6	54.1	54.1	51.9	50.1	46.9	45.2	44.8	43.1	41.2	37.7	35.0	32.5	30.7	27.1	24.3	22.1	20.7
η	0.36	0.38	0.40	0.42	0.44	0.44	0.44	0.44	0.44	0.42	0.40	0.38	0.36	0.34	0.32	0.29	0.27	0.24	0.20
ω	40	44	56	75	95	110	150	190	220	280	400	440	560	750	950	1100	1500	1900	2200
d'_{band}	0.0	0.0	0.0	32.4	145.3	92.1	76.1	215.2	82.2	90.5	51.7	174.4	109.7	218.3	167.5	159.6	42.6	9.3	1.7
d'_{Total}	**495.9**																		

From Table 6, the total detectability index, d'_{total} for the example horn is 495.9. From Section 3.1, the noticeability index, n' = 495.9/50 = 9.9, above the criteria for a 95% likelihood of detection, 4.31.

Using Equations 3 and 4, the $n'L_{measured}$ for the example horn is 10log(9.9) = 10.0 dB; $n'L_{criteria}$ is 10log(4.31) = 6.3 dB, a difference of 3.7 dB. Therefore, the sound output of this horn could be reduced by 3.7 dB while still maintaining a 95% likelihood of detection.

From Reference 1, the L_{eq} measured for the example horn at the compliance measurement location, 100 ft forward of the locomotive, was measured to be 112.3 dB(A). The output of this horn could be reduced by 3.7 dB so that it measures 108.6 dB at the compliance measurement location.

5.0 RESULTS

Figure 2 summarizes the average railroad horn output level necessary for a 95% likelihood of detection for the nominal motor vehicle speed of 41 mph over a range of locomotive speeds.

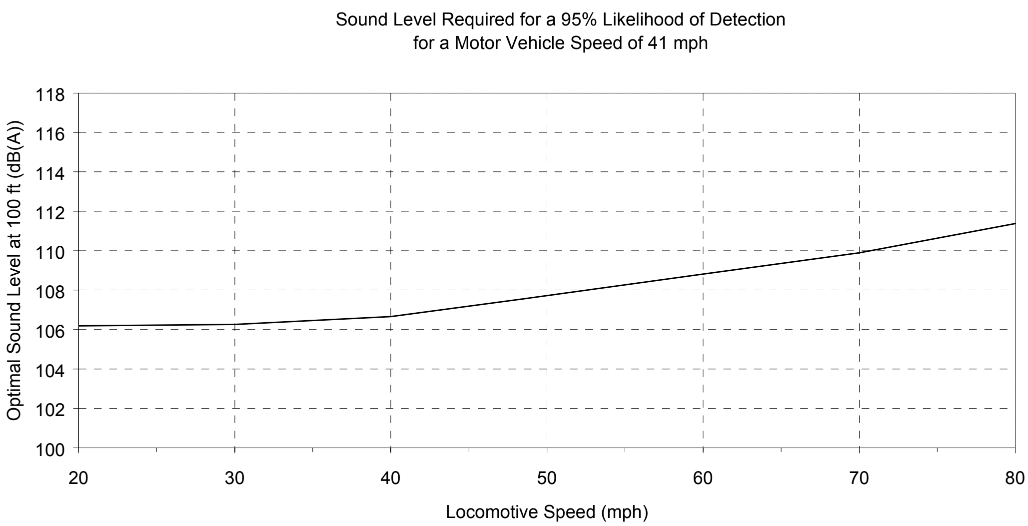

Figure 2. Sound Level Required for a 95% Likelihood of Detection for a motor Vehicle Speed of 41 mph

This graphic shows that, for the nominal speed scenario, described in the example calculation, of a locomotive traveling 48.5 mph and a motorist traveling 41 mph, the average horn should be set conservatively to 108 dB(A) for a 95% likelihood of detection. It should be noted that the limitations of the available data, especially in high-speed situations, result in an uncertainty of the required sound level estimates. To increase the quality of the sound level estimates, interior noise data for a variety of motor vehicles (including buses and trucks) over a range of speeds (e.g., 0 to 50 mph) with optional equipment operating (air conditioning, radio, etc.) should be acquired. In addition, the applicability of aircraft detection criteria to rail horn detection (as discussed in Appendix A) should be thoroughly investigated. This investigation must focus not only on auditory detection, but also on the recognition and understanding of the auditory signal.

APPENDIX A. SIGNAL DETECTION THEORY

The scientific foundation for the general signal detection theory presented in this letter report is an assemblage of research which dates back to the works of Green and Swets in 1966[10]. The derivative work most germane to the discussion presented herein is that by Raslear[11]. The works of Fidell, Bishop, Horonjeff, et. al, [12,13,7,8,9] provide the basis for specifying the general theory of signal detection in terms of auditory detection, or detection by the human ear.

Signal Detection Theory (SDT) can be used to determine the probability (or likelihood) of hearing a horn, termed the probability of a hit [p(Hit)]. This probability is determined using the detectability index, termed d' (dprime). The two are related as follows:

$$d' = z(Hit) - z(FA) \qquad \text{(A1)}$$

Where z(Hit) is the normalized value of p(Hit) and can be obtained from tables of standard normal curve areas. Z(FA) is the normalized value of p(FA), the probability of a false alarm.

Alternately, the detectability index, d', for an acoustical signal is calculated as the vector summation of the band-width-adjusted, signal-to-noise ratio (S/N), over the frequency range of interest (160 Hz to 10 kHz).

$$d' = \sqrt{\left(\sum \frac{\eta S \omega^{.5}}{N}\right)^2} \qquad \text{(A2)}$$

Where η= the efficiency of the observer at a particular frequency
ω =1/3 octave bandwidth
S = the signal level in terms of sound pressure re: 20 microPascals, and
N = the noise level in terms of sound pressure re: 20 microPascals.

While earlier studies have related detection to either A-weighted S/N or a particular one-third-octave band's S/N, the current methodology considers the entire signal, accounting for the relative strength of the signal in each frequency band and the efficiency of the observer to hear sounds at that frequency. Studies of the ability of human observers to detect low-frequency acoustic signals have shown that human efficiency decreases at low frequencies. Reference 14 provides values of η to account for this, ranging from a maximum of 0.44 at 1000 Hz to 0.3 at 100 Hz and 0.2 at 10000 Hz.

Equations A1 and A2 allow us to determine the probability of detection, p(hit) from the signal and noise levels, determined through measurements, if the value of p(FA) is known. The value of p(FA) can be derived from bias, β, which in turn can be determined from the perceived frequency of trains. In the absence of other costs and benefits, β is defined as:

$$\beta = \frac{p(notrain)}{p(train)} \qquad \text{(A3)}$$

Where p(train) is the probability of a train and p(no train) = 1- p(train). β is also calculated as the ratio of the ordinates of the standard normal curve corresponding to z(Hit) and z(FA):

$$\beta = \frac{y_{Hit}}{y_{FA}} \quad \text{(A4)}$$

Where $$y_{hit} = \frac{1}{\sqrt{2\pi}} e^{\frac{-z(Hit)^2}{2}} \quad \text{(A5)}$$

$$y_{FA} = \frac{1}{\sqrt{2\pi}} e^{\frac{-z(FA)^2}{2}} \quad \text{(A6)}$$

Rearrangement of equations A1, A4, A5 and A6 yields

$$d'^2 = z(Hit)^2 + 2\ln\frac{p(notrain)}{p(train)} + z(Hit)^2 \quad \text{(A7)}$$

Thus, value of d' necessary for a 95% likelihood of detection p(hit) can be determined from the value of z(hit) for p(hit) = 0.95, or 1.645, and the probability of encountering a train p(train) (Equation A3), as discussed in the following Section.

A.1 Motorist expectations

The probability of encountering a train should be likened to the motorist's perception of the likelihood of an encounter with a train (perceived frequency). It is assumed that the higher the perceived frequency of trains, the more attentive the motorist will be in listening for the train horn. The perceived frequency of trains can be likened to a probability, and can vary between zero and one.

There are two general types of grade crossing scenarios where a train/motorist encounter might occur. In each scenario, the motorist has a different perception of the likelihood of encountering a train. At crossings with passive warning devices, the motorist may perceive that there is only a small chance of encountering a train. Therefore, the p(train) is set low at 0.1. At crossings where active warning devices are providing indication that a train is approaching, the motorist may have a high expectation of encountering a train. Therefore p(train) is set high at 0.9.

The value for p(train) at a passive crossing (0.1) results in a higher bias, and therefore a higher d' value and resulting S/N necessary for a 95% likelihood of detection, than at an active crossing. In order to simplify analysis and err on the side of safety, only the passive crossing scenario was considered.

By substituting the values of p(train) = 0.1 and p(no train) = 0.9 into Equation A7, the value of d' necessary for a 95% likelihood of detection for a motorist approaching a passive crossing is calculated to be 4.31. This value can be used in Equation A2 to determine the necessary Signal Level. The Signal and Noise levels were determined through measurements as summarized in Section 3.

6.0 References

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