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Administration**

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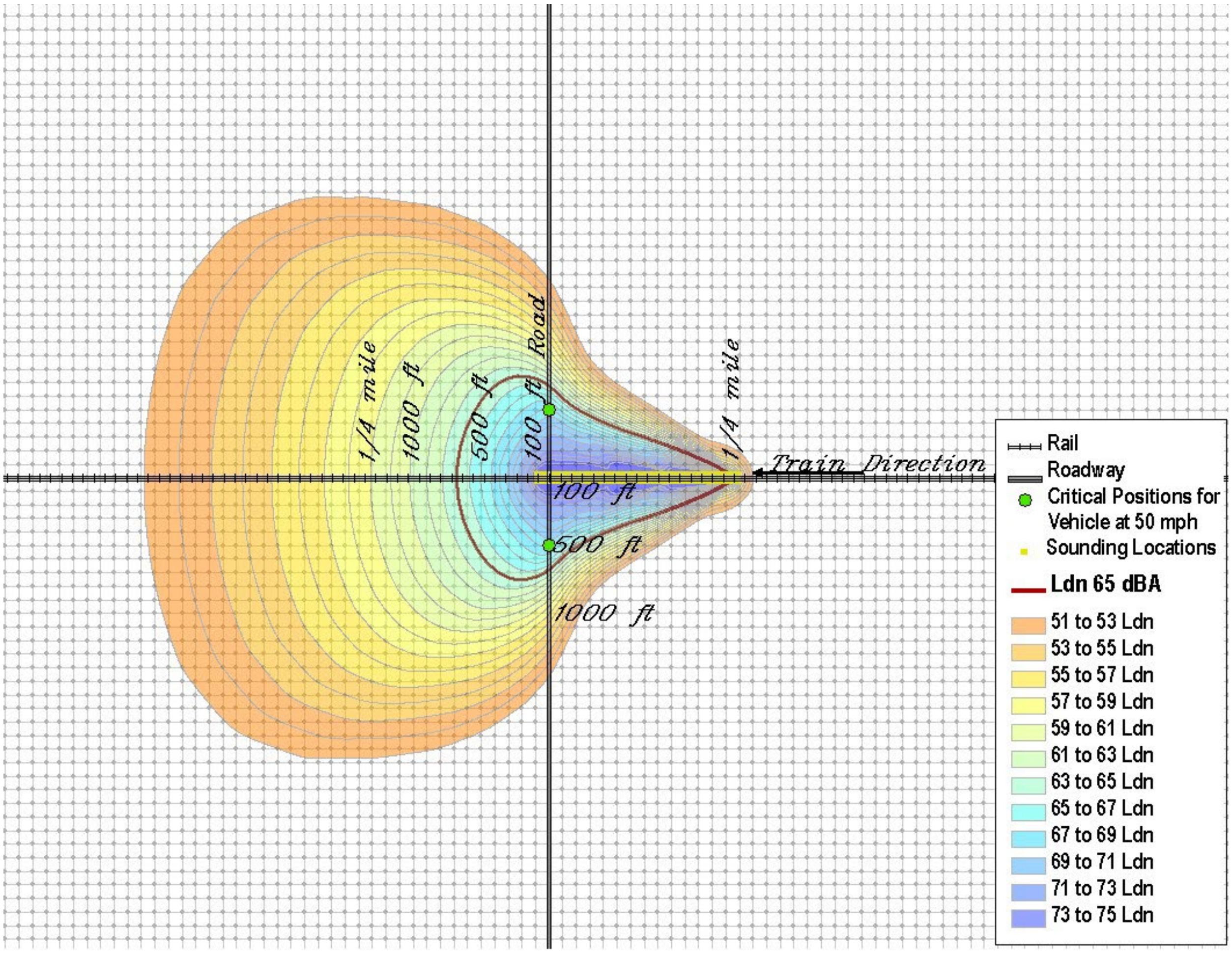
Washington, DC 20590**

Feasibility of a Train Horn with Optimized Directivity: Environmental and Occupational Noise Benefit of an Ideal Train Horn



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This report examines the feasibility of and recommends an acoustical specification for such an optimized horn. The detectability of the horn signal for motorists inside vehicles, the areas of environmental noise impact and occupational noise exposure have been compared for the optimized horn and several typical standard horn systems. It has been found that detectability could be improved and noise impact area reduced by 50 percent or more, depending on amplitude. The optimized horn must have a variable directivity pattern that dynamically changes as a function of train position relative to the crossing to provide substantial noise reduction. Current acoustic source technologies which generate directional sound are examined including “acoustic hailing devices”—a recent technological advancement typically used for military applications, naval communication, and crowd control. Capable of focusing high amplitudes of sound within a narrow beam, acoustic hailing devices have been identified as a feasible means of meeting the required specifications. Finally, the study provides general information concerning cost and implementation of the device.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

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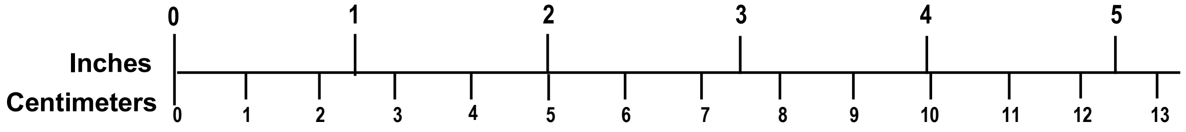

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

From March 2, 2007, to November 30, 2012, the Federal Railroad Administration funded QinetiQ North America, Inc. to examine the feasibility of an acoustical specification for an optimized train horn that improves the detectability of the warning signal for motorists inside vehicles at critical positions along the crossing road, while reducing the area of environmental noise impact. The detectability, noise impact area, and occupational noise exposure have been compared for the optimized horn and several typical standard horn systems. It has been found that detectability could be improved and the noise impact area reduced by 50 percent or more, depending on amplitude. The optimized horn must have a variable directivity pattern that dynamically changes as a function of train position relative to the crossing to provide substantial noise reduction.

Current acoustic source technologies which generate directional sound are examined including “acoustic hailing devices”—a recent technological advancement typically used for military applications, naval communication, and crowd control. Capable of focusing high amplitudes of sound within a narrow beam, acoustic hailing devices have been identified as a feasible means of meeting the required specifications of the optimized horn. Finally, the study provides general information concerning cost and implementation of the device.

Based on existing research, this study includes measurements of standard horn systems, an assessment of the detectability of train horns inside vehicles, measurements of interior noise levels of automobiles, insertion loss properties of automobiles, and measurements of horn noise levels inside locomotive cabs.

1. Introduction

From March 2, 2007, to November 30, 2012, QinetiQ North America, Inc. examined the feasibility of an acoustical specification for an optimized train horn. This horn detects the warning signal for motorists inside vehicles at critical positions along the crossing, while reducing an environmental impact.

1.1 Background

It is estimated that up to 9.3 million persons may be impacted by locomotive horn noise and up to 4.6 million of those may be severely impacted [1]. The National Academy of Engineering Committee on Technology for a Quieter America has indicated that the public would benefit if warning horns were more directional and recommended that research and development related to horn directivity should be undertaken to better understand the effects on safety and benefits to the public [2]. In 2009, there were over 1,900 incidents, 700 injuries, and 240 fatalities at highway-rail grade crossings [3]. A growing concern is the number of train incidents that occur with trespassers. This study examines the feasibility of a highly-directional locomotive-mounted horn. A directional train horn has the potential to focus audible warning signals to desired locations including pedestrians and vehicular motorists at highway-rail grade crossings and workers and trespassers on the railroad right-of-way while minimizing noise to the community and railroad employees in the locomotive cab.

1.2 Objectives

Previous studies have addressed the balance between detectability of audible warning devices and environmental noise impact, but none has recommended specifications for a device which both optimizes safety and minimizes environmental impact [16] [17]. This study is intended to address this research gap and quantify the potential environmental noise impact and occupational noise exposure benefit.

1.3 Overall Approach

Acoustic hailing devices (AHDs) generate a highly directional sound field and are a feasible technology which could approach or meet the acoustical specification of the optimized train horn. AHDs are a specific implementation of a phased array of discrete acoustic sources.

The optimized horn control system requires information on the train position relative to the crossing. This can be obtained easily from the train speed and a defined sounding duration (i.e., 15 to 20 seconds). The amplitude and directivity of the optimized horn would be controlled within the circuitry of the acoustic device depending on train position. Train speed can be obtained from on-board GPS or the speedometer.

The sounding pattern can be controlled manually by the train engineer with typical long- long-short-long signaling or an automated signaling sequence could be played based on the train speed.

AHDs are typically used in military applications and therefore they meet extensive military specifications for exposure to hazards such as temperature, humidity and shock and are expected to be well-suited for railroad applications.

The cost of standard horn systems are approximately $1,000. The costs of existing AHDs are approximately $7,000 to $8,000. The desired solution would be to modify an existing AHD to generate the variable directivity as described. The cost of such an AHD has been estimated to be similar or slightly higher than existing AHDs with a potential for significantly lower costs with large volume production.

Cost-benefits could be taken into account. These costs could be compared to the cost of other noise mitigation measures used against horn noise such as wayside horns and building sound insulation improvements. When assessing the cost-effectiveness of different technologies, the added benefit of allowing voice commands as well as emergency warning tones to be generated with these devices should also be considered. The ability to provide verbal instructions would further improve the safety for workers or pedestrians in the railroad right-of-way.

1.4 Scope

The scope of this research is to modify an existing AHD to generate the variable directivity as described. This could be achieved by design optimization of the horn’s main performance parameters.

1.5 Organization of the Report

Section 2 presents a literature review of applicable Federal regulations and standard audible warning devices; Section 3 examines and recommends the feasibility of an acoustical specification for an optimized device, the methodology used to determine the optimum design and existing technologies for directional acoustic sources; Section 4 includes an assessment of the benefit to environmental noise impact; Section 5 presents the benefit to occupational noise exposure; Section 6 presents cost and implementation issues; while Section 7 includes recommendations for further research. Appendix A includes detectability time histories analyzed for standard horn systems.

2. Literature Review

The Federal Railroad Administration (FRA) regulates the allowable range of noise emissions that locomotive-mounted and wayside-mounted horns must generate [14]. The regulations specify the minimum (96 dBA) and maximum (110 dBA) overall A-weighted noise levels measured 100 feet forward of the locomotive. The regulation specifies the equipment and measurement procedures required to test horn systems. The regulation also specifies that the warning device may not be sounded beyond 1/4-mile from the grade crossing and should be sounded for a total of 15 to 20 seconds, with a maximum of 25 seconds, using a long-long-short-long pattern. The engineer should also sound the horn until the first locomotive has passed through the crossing.

Wayside horn noise limits are regulated by FRA to a minimum of 92 dBA and a maximum of 110 dBA. Wayside horns must be sounded for a minimum of 15 seconds with the horns oriented towards approaching traffic. Adequate signaling to notify the locomotive engineer of whether the wayside horn is functional must also be provided.

Data referenced in support of the regulation describe typical audible signals (i.e., primary tones and harmonics) and typical directivity patterns; however, the regulation does not explicitly regulate either the audible signal content or the allowable amplitude at directions other than forward of the locomotive. This study recommends an optimized train horn whose acoustic specifications comply with FRA regulations.

A British Railway Group Standard [18] on the Audibility Requirements for Trains specifies the range of allowable overall A-weighted or C-weighted noise levels based on train speed. The standard also specifies the frequency of tones that must be sounded for two-chime and three-chime horns.

FRA regulates occupational noise exposure for railway workers [19]. A hearing conservation program must be implemented for railway workers whose 8-hour time-weighted average (TWA) noise level exceeds 85 dBA and the allowable limit for noise exposure is a TWA level of 90 dBA. This regulation also specifies static noise measurements inside locomotives that can be conducted to find “bad actors” which may generate levels in excess of the noise standard. For workers inside the locomotive cab, the most significant noise exposures have been found to be the diesel prime mover at high throttle setting, horn noise and dynamic braking [13]. Studies have shown that railway workers are not typically exposed to noise levels in excess of the regulations [13] [20] [21]. This study provides a general assessment of the potential reduction in in-cab noise levels for an optimized train horn device.

2.1 Standard Audible Warning Devices

This section provides a general background on standard audible warning devices used on FRA-compliant rail lines. Devices include air pressure horns on-board locomotives, automated wayside horns which are stationary horns mounted at grade crossings, and horns that have been designed with some degree of directivity.

2.1.1 Standard Locomotive Horn Systems

Standard locomotive horn systems in the United States generally include three and five-chime air pressure horns. Individual horns may be directed all in one direction or some of the horns may point forward and some backward. The latter configuration is termed a bi-directional horn. The major manufacturers of train horns include Air Chime Limited, Leslie Company, and Buell Air Horns.

Under free field conditions, air pressure horns generate a relatively omni-directional pattern of sound. The actual directivity pattern of standard horn systems depends on its location mounted on a locomotive. Detailed measurements of five standard horn systems mounted on two different locomotives in up to four different mounting locations have shown that radiation patterns of standard train horns may vary up to 10 dBs [6] [8]. In particular, horns mounted in the center of the long hood can be up to 10 dBs lower forward of the locomotive compared to cab-roof or knuckle-mounted horns due to the acoustic shielding provided by the locomotive body. These measurements included overall A-weighted levels at 45 degree increments around the locomotive, 1/3-octave band spectra forward, wayside and rear of the locomotive and in-cab noise measurements with windows open and closed.

2.1.2 Automated Wayside Horns

Wayside horns are mounted at crossings and direct sound down the roadway to alert motorists and pedestrians. Signaling from the stationary horn to the locomotive must be provided for the engineer to be assured the horn will be sounded. Wayside horns are capable of significantly reducing environmental impact by reducing noise levels 10 dBs or more [22]–[25]. Wayside horns generate a different warning signal than on-board trains. The amplitude of the signal typically does not increase and decrease with the location of the train. This has been shown to potentially startle those near the horns. Wayside horns do not recreate the Doppler Effect, the shifting in frequency due to the movement of the noise source, an important signature of on-board trains which assist motorists and pedestrians with localizing the trains approach.

Wayside horns can be relatively directional and focus the sound within the roadway corridor and away from abutters. A study in Fort Worth, TX, showed that wayside horns can have directivity with amplitudes reduced 10 to 17 dBs at angles between 67.5 and 180 degrees [24].

2.1.3 Directional Horn Systems

The directivity of locomotive-mounted horns has been of interest to many in the rail industry as a potential means of limiting environmental noise exposure. An existing study included the design and implementation of a directional horn for the Los Angeles County Metropolitan Transit Authority (MTA) as a “proof of principle” demonstration [26]. This device was a 10-speaker linear array of horns mounted on the front of a test vehicle. The horn focused a majority of its sound energy within a beam approximately 90 degrees (0 degrees +/- 45 degrees). The radiation between 15 and 30 degrees from forward of the locomotive was reduced approximately 10 to 20 dB and for 30 to 135 degrees the array would be down approximately 20 to 25 dBA. This directional horn generated a single directivity pattern. Interestingly, the existing MTA horn systems are relatively directional. The detectability of this horn at grade crossings was not assessed.

A highly-directional dual-mode electronic siren was developed and tested by the National Bureau of Standards in 1978 [27]. The horn included four siren loudspeakers and it was capable of switching from a strong narrow beam to a broader beam. The phase array device generated a maximum sound level that was 7 to 10 dBA higher in the desired directions than a single acoustic element.

An audible warning device with constant directivity limits both the safety of the audible warning and the improvement to environmental noise. A device can have a narrower beam width when sounded at further distances from the crossing (i.e., 1/4-mile) and a wider beam width as the train passes through the crossing. As discussed in Section 3.2, this factor is considered in the recommended design of an optimized train horn.

2.1.4 Emergency Signals

Many light rail transit and heavy rail transit trains have different horn levels (i.e., high horn and low horn) as well as an emergency signal which is generally a high-amplitude high-frequency signal. Diesel-electric passenger and freight locomotives, on the other hand, have an air pressure horn and bells, but no emergency signal. A study undertaken for Transport Canada assessed the position of locomotive horns and recommended the use of emergency-only or two-level horns [28]. This study also recommends that an optimized train horn must have an emergency signal.

3. Acoustical Specification of an Optimized Train Horn

3.1 Definitions

Sound – Sound is the rapid fluctuation of pressure above and below ambient levels. Sound is measured in decibels with a reference of 20 micro-Pascals.

Noise – Noise is used to describe unwanted sound.

A-weighting – The human ear does not respond equally to identical noise levels at different frequencies. Although the normal frequency range of hearing for most people extends from a low of about 20 Hz to a high of 10,000 to 20,000 Hz, people are most sensitive to sounds in the voice range, between about 500 to 2,000 Hz. Therefore, to correlate the amplitude of a sound with its level as perceived by people, the sound energy spectrum is adjusted, or "weighted." The weighting system most commonly used to correlate with the pedestrian and motorists' response to noise is "A-weighting" (or the "A-filter") and the resultant noise level is called the "A-weighted noise level" (dBA). A-weighting significantly de-emphasizes those parts of the frequency spectrum from a noise source that occurs both at lower frequencies (those below about 500 Hz) and at very high frequencies (above 10,000 Hz) where most people do not hear as well.

Amplitude – Amplitude is the intensity of sound and relates to the perceived loudness. Typically, sound amplitudes that people experience range from the threshold of hearing, 0 dBA, to very high levels exceeding 100 dBA.

Frequency – The rate of repetition of sound pressure oscillations as they reach our ears, frequency, is often termed "pitch." Frequency is expressed in units known as Hertz ([Hz] and is equivalent to one cycle per second). The distribution of sound energy as a function of frequency is termed the "frequency spectrum." The frequency of sound is commonly reported in octaves or 1/3-octave bands. Octave bands are ranges of frequency where the highest frequency in the band is twice as great as the lowest.

Directivity – Directivity is the variation of amplitude and/or frequency of an acoustic source as a function of direction. If a source radiates sound equally in all directions, it is considered to be omni-directional.

Day-Night Sound Level (Ldn or DNL) – The Day-Night Sound Level (Ldn or DNL) represents a noise dose as it occurs over a 24-hour period. It is a cumulative metric that takes into account the amplitude of the noise events, their duration, how often they occur and what time of day they occur. In determining DNL, it is assumed that the A-weighted levels occurring at night (10PM to 7AM) are 10 dB louder than they really are. This 10-dB penalty is applied to account for greater sensitivity to nighttime noise, and the fact that events at night are often perceived to be more intrusive because the background ambient noise at night is less than the ambient noise during the day.

3.2 Design Factors of an Optimized Train Horn

This section describes the design factors considered in specifying the optimized train horn. Analyses include determining the critical angles that a horn must propagate the signal to protect particular segments of crossing roads and the resulting variable directivity of the horn.

The detectability of the horn signal for motorists inside vehicles have been compared for several typical standard horn systems, an optimized horn with variable directivity and variable amplitude, a "modified" horn with a static directivity pattern sufficient to direct sound to the widest critical angle required, a horn with variable directivity and amplitude maximized for safety and a horn with variable directivity and amplitude minimized for noise impact reduction.

3.2.1 Horn Critical Angles

Train horns must generate an audible warning signal which can be detected by railway workers and trespassers in the railroad right-of-way and pedestrians and motorists on crossing roads.

Warning railway workers, trespassers, and pedestrians requires having a sufficient signal generated forward of the locomotive. Since pedestrians travel at a relatively low speed, there is not a need to generate sound very far to the side of the tracks. Motorists, on the other hand, may be traveling at high speeds and train horns must therefore generate sufficient signals further away from the tracks. Specifically, motorists approaching a grade crossing must notice a train approaching, react to the situation, initiate the stopping of their vehicle and then stop the vehicle according to the dynamic properties of its motion.

The critical distance from the crossing that a motorist must notice a train increases with vehicle speed. Further, the train audible warning signal must be noticeable for the entire segment of road between this critical position and the train tracks. These critical positions have been computed using a similar methodology to that in prior studies [5] [7] [29] and is based on the vehicle speed, the motorist reaction time, the minimum stopping distance of the vehicle assuming it is traveling on wet pavement [30], the critical track zone and the vehicle length.

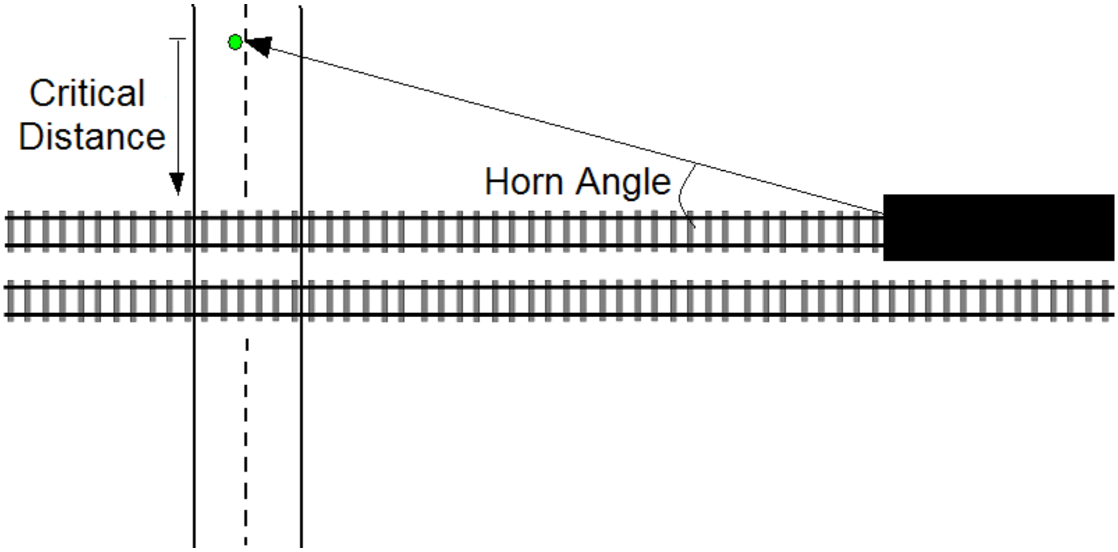


Figure 1. Critical Distance and Horn Angle Geometry

The critical distance for the driver to notice the train horn is computed as follows and shown in Figure 1:

$$D_{cr} = V_m^{\ 2}\,(m/s)/20(f \pm g) + CTZ\,(m) + Vehicle\ Length\ (m) + V_m(m/s) * Driver\ Reaction\ Time,$$

where V_m is the vehicle velocity in meters per second, f is the skidding friction coefficient and g is the pavement grade. Assuming a driver reaction time of 2.5 seconds, no grade, a coefficient of friction from 0.31 to 0.35 depending on vehicle speed, a critical track zone (CTZ) of 9.14 m and a vehicle length of 5.8 m, the critical positions are 160, 248, 360 and 499 feet for vehicle speeds of 20, 30, 40 and 50 mph, respectively.

The angles which a train horn must cover to provide a sufficient signal to these critical positions vary according the train position. At 1/4-mile from the crossing, the angles are minimized and when the first locomotive is entirely through the crossing, the angles are maximized. Figure 2 shows these critical angles for vehicle speed of 20, 30, 40 and 50 mph. This assumes the horn is mounted in the center of the long hood approximately 30 feet back from the front of the locomotive. This figure shows that the narrowest angle that must be maintained (at 1/4 mile from the crossing) is 14 degrees (0 degrees +/- 7 degrees) for cars traveling at 20 mph. The maximum angle that must be maintained (near the crossing) is 210 degrees for cars traveling at 20 mph. Except when the locomotive passes through the crossing, the greatest angles must be maintained for cars traveling at 50 mph and thus the analysis of environmental benefit is based on the directivity needed for cars at 50 mph. Even though the angle needed when the locomotive is going through the crossing is greatest for cars at 20 mph, the distance associated with this position is significantly less than the distance for cars traveling at 50 mph.

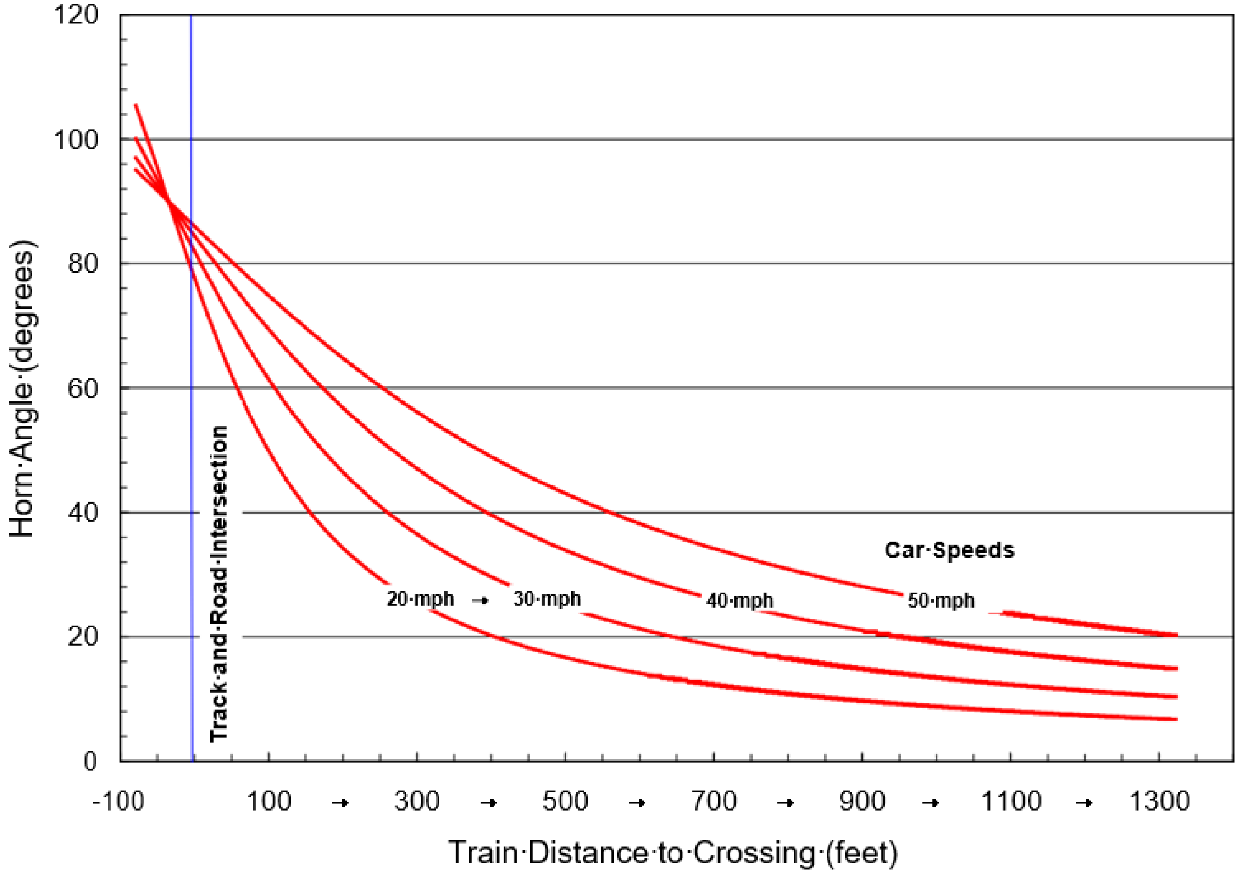


Figure 2. Critical Horn Angle vs. Train Location (for vehicles at 20, 30, 40 and 50 mph)

3.2.2 Directivity

The horizontal directivity of the optimized horn is specified to vary according to the distance of the train to the crossing. To protect motorists driving at 50 mph on crossing roads, the directivity required to alert motorists in time to stop their vehicle before the crossing is as narrow as 42 degrees (0 degrees +/- 21 degrees) when a train is 1/4-mile from the crossing, and as wide as 198 degrees (0 degrees +/- 99 degrees) when the first locomotive is entirely through the crossing.

The main beam of sound generated by the horn is assumed to be constant throughout the required angle and then drop off at a rate of 2/3 of a decibel per degree meaning that the signal would be 10 dBs down 15 degrees beyond the extent of the main beam and 20 dBs down 30 degrees beyond the extent of the main beam. The maximum reduction of the optimized horn at angles beyond the main beam including the radiation rear of the horn is assumed to be 25 dBs on an overall A-weighted basis. Figure 3 shows the directivity pattern of the optimized horn at several representative locations along the track. The directivity is specified to change relatively continuously (e.g., every 100 to 1,000 ms).

With flat surrounding terrain, the vertical directivity required to provide sufficient signal to pedestrians and motorists at a range of distances could be relatively narrow, but does not need to be. Maintaining a narrow vertical directivity could potentially provide greater benefit to in-cab occupational noise exposure. However, since the optimized horn would likely be mounted on the top of the locomotive at a height of approximately 16 feet, the vertical directivity must be sufficient to provide adequate signal to those close to the locomotive and handle elevation changes to the surrounding terrain. The vertical directivity would generally not affect the environmental noise exposure except perhaps under high wind conditions, temperature inversions or high-speed trains which could cause aerodynamic effects to the sound propagation. Therefore, the vertical directivity of the optimized horn should be similar to the horizontal directivity to provide adequate coverage. For acoustic sources with relatively similar height and width dimensions, it is typical that vertical directivity would be similar to horizontal.

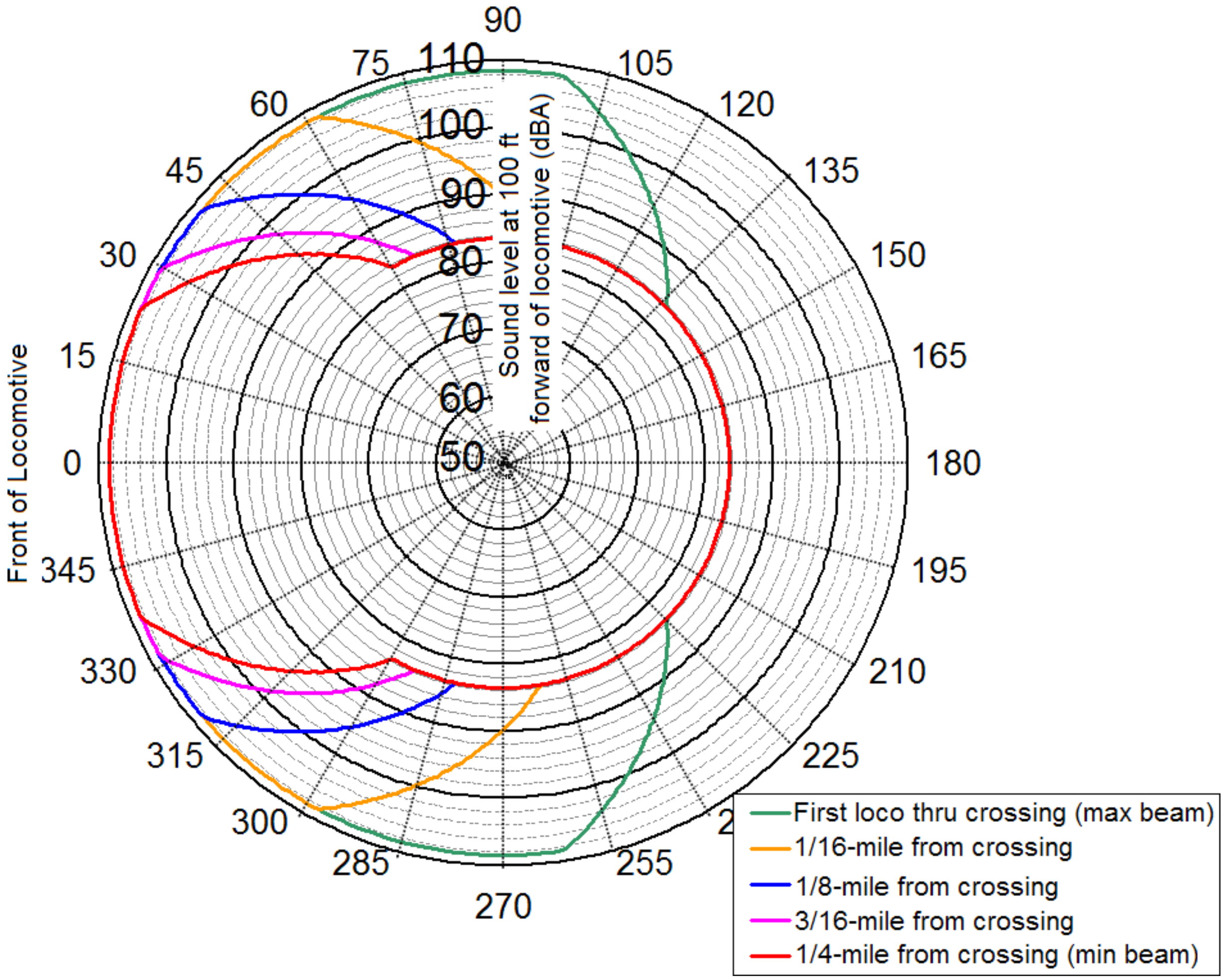


Figure 3. Horn with Variable Directivity for Several Train Locations Along Track

3.2.3 Horn Detectability

To assess one aspect of the safety provided by horns, the detectability inside automobiles of standard horn systems measured by the Volpe National Transportation Systems Center's (Volpe) acoustics group [6] and horns with variable directivity including the optimized design have been compared. While most previous studies have assessed the detectability at the critical position of the vehicle and the corresponding critical position of the locomotive, this analysis computes the detectability at the critical vehicle position and all train locations between 1/4-mile from the crossing and when the first locomotive is entirely through the crossing (totaling approximately 1,400 feet). The detectability has been computed at critical positions inside vehicles traveling at 20, 30, 40 and 50 mph. The critical positions of the vehicle are where the motorist must notice a train is approaching to have sufficient time to react and stop the vehicle as described in Section 3.2.1. The detectability calculation is based on horn levels propagated to the outside of the vehicle, the insertion loss or outdoor-to-indoor noise reduction of typical vehicles, the corresponding horn noise levels inside the vehicle, background noise levels inside the vehicle and the estimated auditory system noise.

Sound Propagation

As sound propagates from a source through the air it attenuates in amplitude. There are several factors that determine the rate at which sound attenuates including the type of source, distance from the source, atmospheric conditions, and ground effect. Simple acoustic sources radiate sound such that the acoustic waves spread out spherically. The further away sound waves propagate from the source, the spherical sound wave covers a larger volume and the acoustic energy gets spread out. When the acoustic energy gets spread out, it drops in amplitude. For a simple source, this geometric spreading causes sound pressure levels to be reduced by 6 dBs for each doubling of distance.

Atmospheric conditions can affect sound propagation, especially over longer distances. Air absorbs some of the acoustic energy a source generates and the rate at which this absorption occurs depends primarily on the temperature and relative humidity. Wind conditions can also affect sound propagation by causing sound waves to refract, or bend, upwards or downwards and increase or decrease the sound that reaches a receptor. For sound propagation from sources on the ground to receptors on the ground, the type of ground cover affects propagation. Soft porous ground covers such as grass or snow will impede the sound wave propagation while hard reflective surfaces such as water and pavement provide less impedance. These effects on sound propagation depend on the frequency of sound. For example, atmospheric absorption generally reduces high-frequency sound more than low-frequency sound.

Two methods have been used to model sound propagation for this study. For modeling the time history of received sound levels and detectability of train horns at critical positions on the roadway, sound propagation has been computed based on spherical spreading and atmospheric absorption. Atmospheric absorption has been computed according to the Society of Automotive Engineers (SAE) Standard ARP-866A with conditions of 77 °F and 70 percent relative humidity. For modeling the environmental noise impact contours, Soundplan™, commercially-available sound propagation software, has been used with the Nordic General Prediction Model propagation algorithms. Both modeling approaches assume the surrounding terrain is soft flat ground. No adjustments for acoustic shielding from building rows and trees or refraction from wind gradients (i.e., from the atmosphere or from the moving train) have been included.

The modeling uses the static frequency content of the train horns and does not include the shift in frequency due to the Doppler Effect. Because sound propagation depends on the frequency content of the source, the Doppler Effect can affect these calculations depending on the train speed. At higher train speeds, the Doppler Effect causes the frequency of the horn to shift. For the modest train speeds analyzed in this study, this is not considered to be a significant factor.

Insertion Loss of Vehicles

To determine the amplitude and frequency content of the horns inside of vehicles, researchers must quantify the typical insertion loss, or outdoor-to-indoor noise reduction of vehicles. The following summarizes the insertion loss of vehicles measured in recent studies:

- The insertion losses of seven 1990–1991 cars were measured at a range of sound incident angles with windows closed by the Volpe Acoustics Group [5]. Generally, the insertion loss of these vehicles was 10 to 20 dBs below 315 Hz. Between 315 and 8,000 Hz, the insertion loss ranged from 20 to 40 dBs and, at 10,000 Hz, the insertion loss was 40 to 45 dBs [5]. The average insertion loss was used in this analysis and in the FRA report "Determination of a Sound Level for Railroad Horn Regulatory Compliance" [7].

- Figure 4 shows the average insertion loss spectrum used in this analysis. The overall A-weighted insertion loss based on the Nathan K-5-LA horn spectrum is approximately 26 dBA.
- The insertion losses of six 1998–2007 cars were measured with windows open, closed and cracked open approximately 1 inch and used to project interior noise levels from train horns [11]. These measurements show similar insertion loss characteristics to those conducted by the Volpe acoustic group; however, insertion loss values were generally greater than 40 dB at frequencies 1,600 Hz and above. With windows closed the overall A-weighted insertion loss for typical train horn spectra ranged from 31 to 37 dBA with an average of 35 dBA. In comparison to measurements by the Volpe acoustic group, these data indicate that newer vehicles may provide greater noise reduction.
- A study conducted to assess the improvement in noise reduction for laminated side glass reported insertion loss values similar to those measured in studies by the Volpe acoustics group and Raymond Brach [12]. Insertion loss values were typically 15 dB at 160 Hz increasing steadily to 35 dB at 1,600 Hz. Above 1,600 Hz, the insertion loss values varied as a function of the laminated glass treatments. The treatment providing the greatest noise reduction maintained insertion loss values of 40 to 45 dBs above 1,600 Hz. This study is an example of an improvement to modern vehicles that helps to provide greater noise reduction.

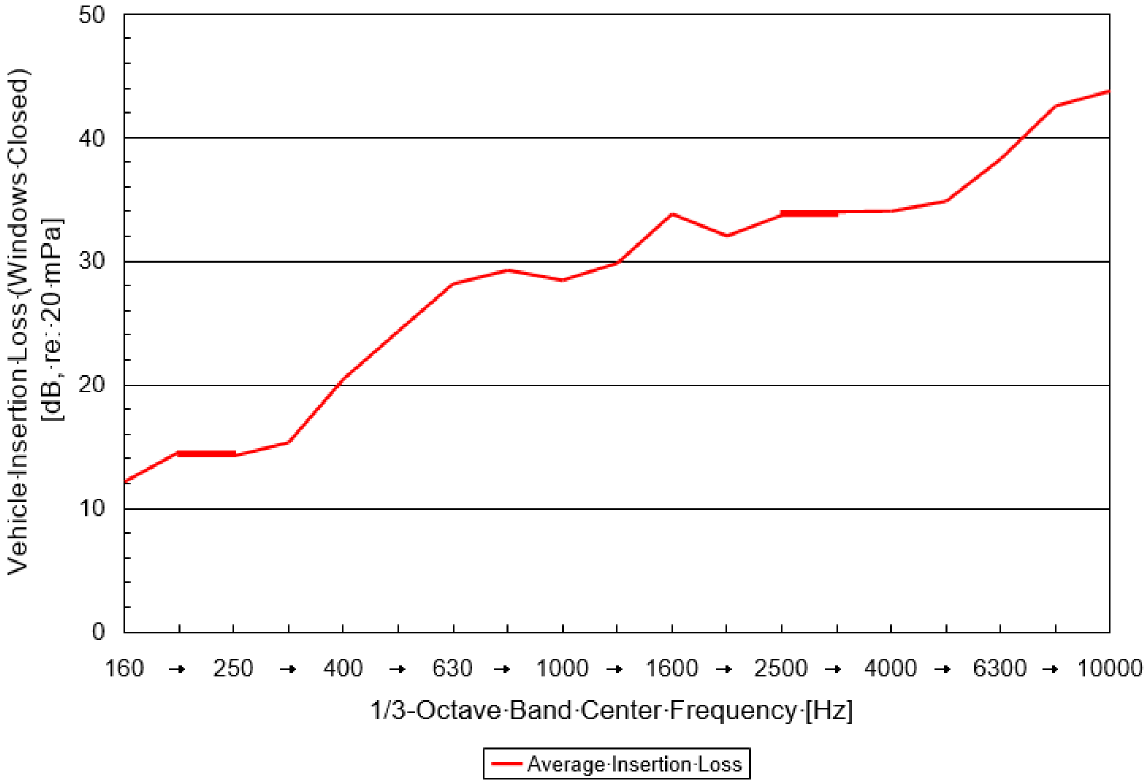


Figure 4. Typical Vehicle Insertion Loss (windows closed)

Vehicle Interior Background Noise Level

The SAE Standard J1477 establishes test procedures for measuring interior noise levels of light vehicles. The International Standards Organization (ISO) also has a measurement standard, ISO 5128:1990, specifying the conditions for collecting interior noise data for all kinds of road vehicles. Several studies have reported interior noise levels inside automobiles with windows open and closed, at varying speed and on different types of pavement.

The following summarizes the interior noise levels measured in these studies:

- The Volpe acoustics center measured the interior noise levels of seven 1990-model automobiles in accordance with SAE J1477. Overall A-weighted interior noise levels for vehicles at 30 mph with windows closed, radio off and interior fans off ranged from approximately 52 to 62 dBA with an average of 57.4 dBA [5]. This average interior level was used in this analysis and Rapoza & Fleming (2002).
- Interior noise levels for 15 vehicles traveling at 70 mph reported in automotive magazines for 1992 to 1993 vehicles ranged between 61 and 73 dBA with an average of 69 dBA [5].
- Interior noise measurements of an individual vehicle were conducted in accordance with SAE Standard J1477 to characterize the noise levels of numerous pavement types [9]. This study showed that interior noise levels ranged from 65.9 to 75 dBA and averaged 69 dBA at 62 mph.
- A Bolt Beranek and Newman study referencing popular science studies of over 150 automobiles manufactured from 1970 to 1975 show average overall noise levels of 63.4 dBA for automobiles at 30 mph on smooth road, 73.5 dBA at 30 mph on rough road and 72.0 dBA at 60 mph on smooth road. These noise levels are considered to be representative mostly of cars with windows closed. Based on these results the U.S. Environmental Protection Agency determined that the typical cruising noise levels inside automobiles range from 62 dBA to 83 dBA with an energy mean of 74 dBA [10].

The average interior noise level of 57.4 dBA measured by Volpe at 30 mph has been used in this study for assessing detectability at all vehicle speeds. While this interior noise level is relatively low compared to other data available for higher vehicle speeds, it is chosen because the dataset includes 1/3-octave band spectra which are necessary for computing detectability. Figure 5 shows the vehicle interior background noise spectrum as part of a representative detectability analysis.

Detection Theory

The detectability of the train horns as observed inside a typical motor vehicle has been assessed using a similar methodology and assumptions as the Volpe acoustics group in their report on the "Determination of a Sound Level for Railroad Horn Regulatory Compliance" [7]. This methodology is based on psychoacoustic theory of the ability for humans to detect a sound based on the background noise levels, the estimated human threshold of hearing and the amplitude of the noise source to be detected [31]. Detectability is essentially a calculation of the signal-to-noise ratio between the source signal and the background noise plus the estimated human auditory system noise. Two different limits are used in characterizing the detection of noise sources; the limit of "audibility" is considered to be the lowest level that a human with normal hearing can detect a source when purposely listening for the source and "noticeability" is considered to be the lowest level that a human can detect a source when not awaiting or expecting an event to occur.

The metric used to measure the detectability of a noise source is called "d-prime." The d-prime metric reported in this study is 10 times the logarithm of the sum of the squared individual d-primes in all 1/3-octave bands between 160 and 10,000 Hz. The limit of audibility used in this analysis is a d-prime value of 7, the limit of noticeability is a d-prime value of 17 and the limit of a 95% Likelihood of Noticeability is a d-prime value of 23.3 for a passive grade crossing. A passive grade crossing is one where there are no crossing bells or gates.

The following information must be known to calculate detectability: reference levels of the horns, sound propagation conditions (i.e., distance from source to receiver, ground type and atmospheric conditions), the typical insertion loss (i.e., outdoor-to-indoor noise reduction) of vehicles and typical background noise levels inside vehicles. This information allows us to project the audible warning signal to the inside of vehicles and compare it to the background noise. As shown in Figure 5, detectability is calculated by adding the estimated auditory system noise to the background noise inside the vehicle and comparing this to the horn noise inside the vehicle.

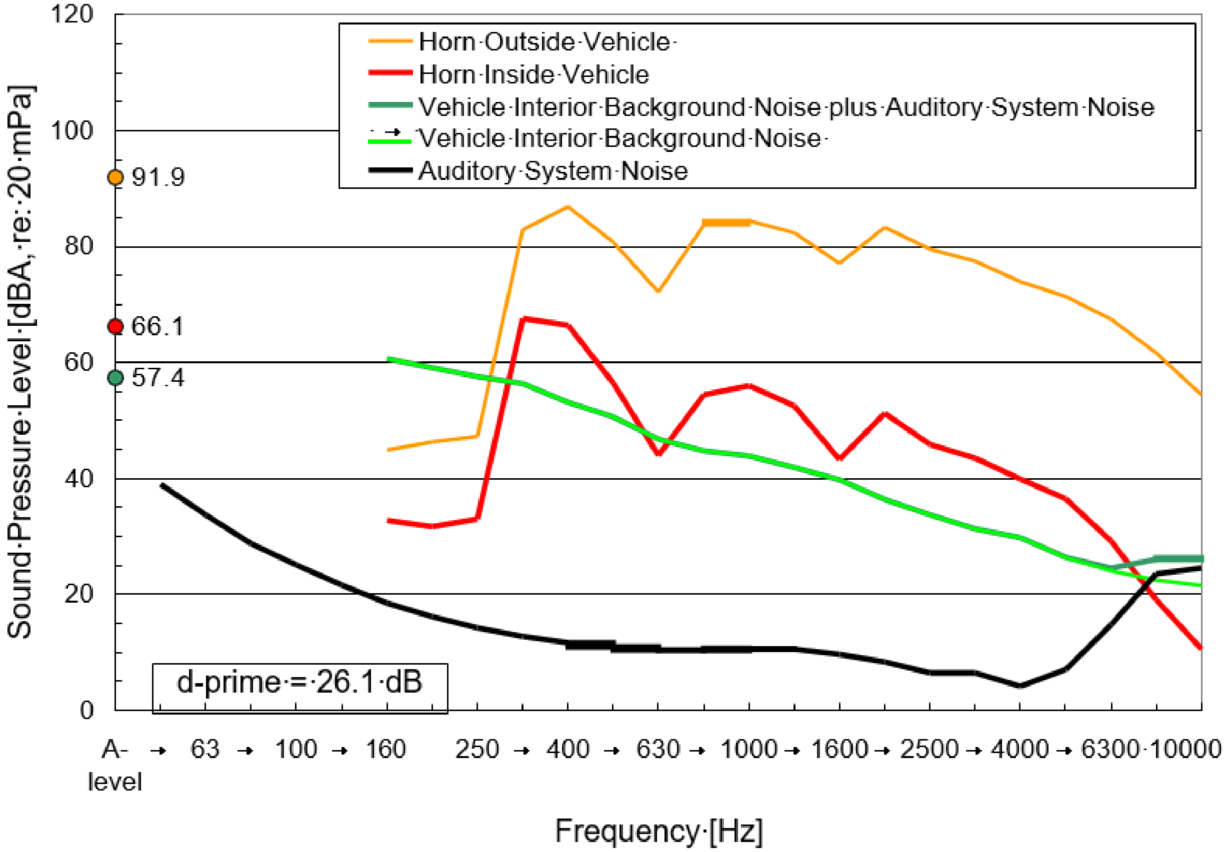


Figure 5. Detectability of Train Horn Inside Vehicle

Detectability Results

Instead of computing time audible, which depends on train speed and sounding pattern, we compute the total distances of the train along the sounding event that different detectability goals are met. The results include the total distance over which each horn would be audible, noticeable and 95 percent likely to be noticeable. As shown in the example provided in Figure 6, detectability is shown as a function of train position. This figure shows the detectability for a standard K-5-LA horn center-mounted on a GP40 for critical positions of the vehicle at 20, 30, 40, and 50 mph.

The figure also shows the directivity pattern of the horn in the lower left corner. This figure shows how detectability is similar for all vehicle speeds when the train is 500 feet or greater from the crossing. Closer than 500 feet to the crossing, the detectability depends significantly on the vehicle speed and the respective distances and angles that the horn must propagate. For vehicles at 20 mph, the detectability is greatest since the critical distance at this speed is 160 feet. For vehicles at 50 mph, the detectability is lowest since the critical distance is 499 feet. It is important to note that the detectability calculations use the same interior car background noise and that actual background noise levels would be expected to increase for higher vehicle speeds. This would cause greater differences in detectability as a function of vehicle speed than shown.

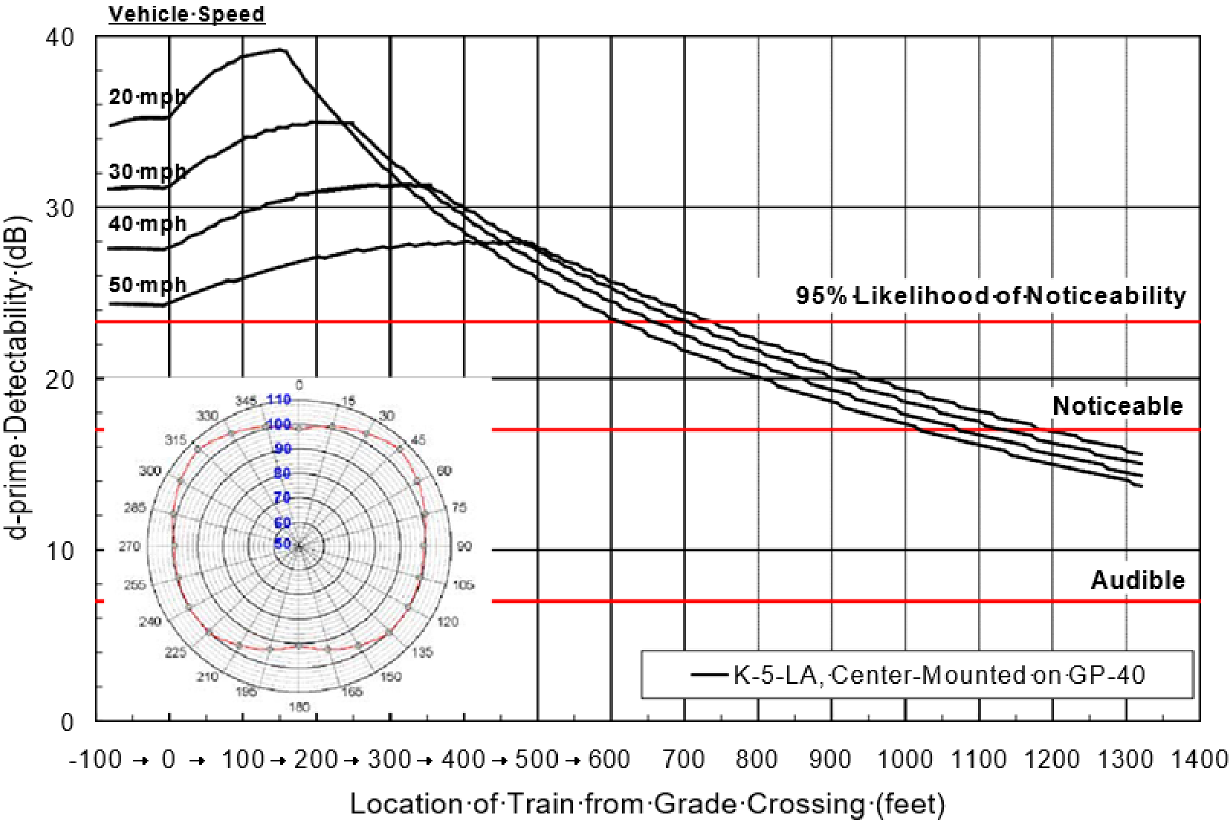


Figure 6. Detectability of Standard Horn (K-5-LA Center-Mount GP40) vs. Train Location and Vehicle Speed

The detectability of the following horns was analyzed:

- Eight typical standard horns
- A "modified" horn with a static directivity pattern sufficient to direct sound to the widest critical angle required
- A horn with variable directivity and amplitude maximized for safety (110 dBA at 100 feet forward of the locomotive)
- A horn with variable directivity and amplitude minimized for greatest noise impact reduction (96 dBA at 100 feet forward of the locomotive)
- An optimized horn with variable directivity and amplitude that ranges from 110 dBA to 104.6 dBA at 100 feet forward of the locomotive to both improve detectability and reduce the area of noise impact

Figure 7 presents the detectability for eight standard horns (grey lines), a directional horn with amplitude maximized for safety (top blue line), a directional horn with amplitude minimized for noise reduction (bottom blue line), the modified horn (black line), and the optimized directional horn (green line). The modified horn has the same detectability as the average of all standard horns. This figure shows that there is a wide range of detectability between the minimum (96 dBA) and maximum (110 dBA) limits to the horn. Table 1 presents a summary of the results, that could be highlighted as follows:

- Standard horns, on average, are audible for the entire sounding event (1,400 feet), noticeable for 1,263 feet and 95% Likelihood of Noticeability for 533 feet.
- The modified horn has the same distances of detectability since it is assumed to maintain the same signal and amplitude to the critical position of the vehicle and then reduce emissions at wider angles.
- The directional horn designed for maximum safety (110 dBA) is audible and noticeable for the entire sounding event and 95% Likelihood of Noticeability for 1,028 feet. This device generates a signal with a maximum detectability 8 dBs above the threshold for 95% Likelihood of Noticeability.
- The directional horn optimized for improved safety and reducing noise impact has the same distances of detectability as the device designed for maximum safety, however, the maximum detectability is 3 dBs above the threshold for 95% Likelihood of Noticeability.
- The directional horn designed for minimum noise impact (96 dBA) is audible for 1,275 feet of the sounding event, noticeable for 210 feet, but does not reach a detectability level above the threshold for 95% Likelihood of Noticeability.

With the aforementioned directivity and amplitude, the optimized horn provides audibility and noticeability to motorists traveling up to 50 mph for a longer distance than any of the standard horn systems analyzed and the same distance as the directional horn with maximum amplitude. Appendix A presents the detectability time histories of standard train horns at all vehicle speeds.

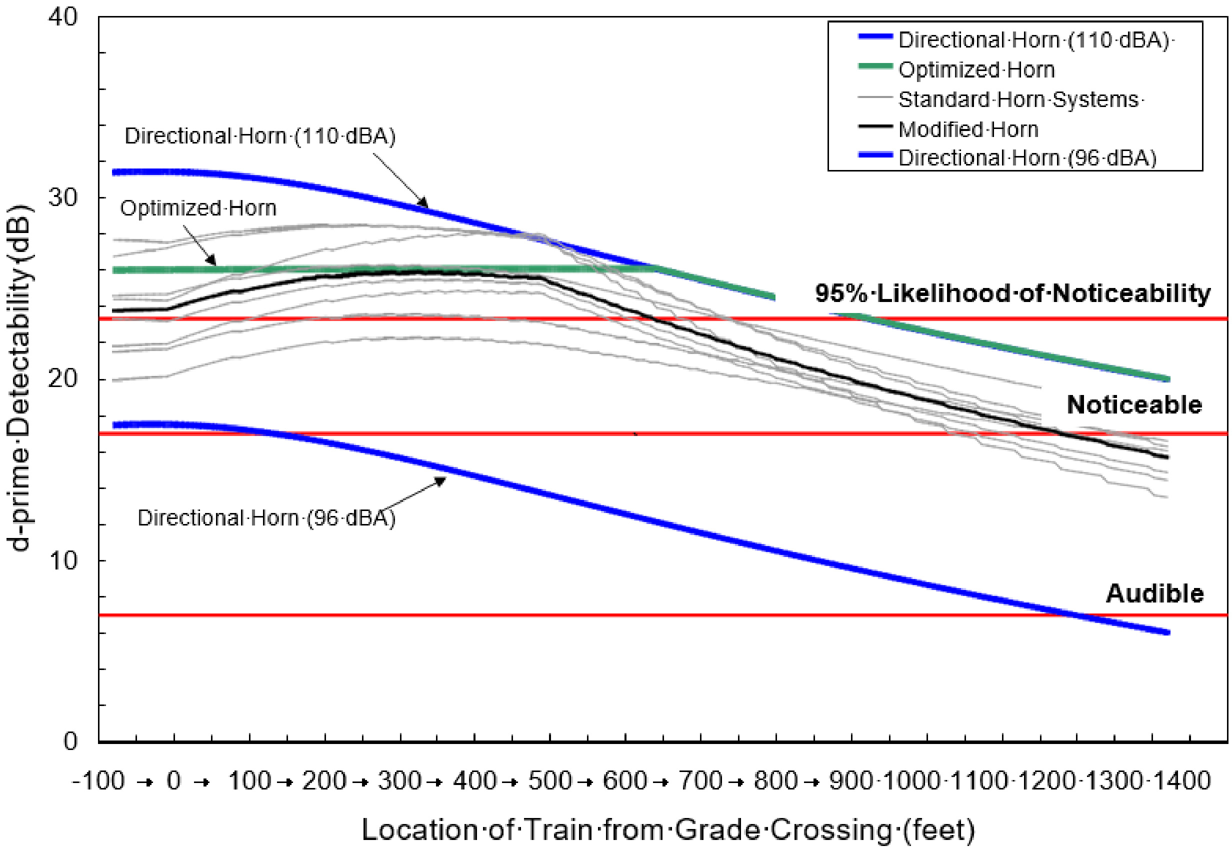


Figure 7. Detectability of Directional Train Horns and Standard Horns vs. Train Location for Vehicles at 50 mph

Table 1. Summary of Distances Meeting Detectability Limits for Standard Horns, Modified Horn and Directional Horns (maximum safety, maximum noise benefit and optimized)

			Total Distance Meeting Detectability for Motorists at 50 mph (feet)		
Horn	**Mounting Location**	**Locomotive**	**Audible**	**Noticeable**	**95% Likelihood of Noticeability**
K-5-LA	Center	GP-40	1,400	1,260	810
RS-3L-RF	Center	GP-40	1,400	1,180	600
RS-3L	Center	GP-40	1,400	1,140	470
K-5-LAR24	Center	GP-40	1,400	1,320	810
K-5-LAR24	Cab Roof	GP-40	1,400	1,390	350
K-5-LA	Cab Roof	GP-40	1,400	1,330	210
RS-3L	Cab Roof	GP-40	1,400	1,250	0
K-5-LA	Cab Roof	MAC-60	1,400	1,400	810
K-5-LA	Center	MAC-60	1,400	1,100	740
Average of Standard Horns			**1,400**	**1,263**	**533**
Modified Horn (Static Directivity)	Center	n/a	1,400	1,263	533
Directional Horn (Optimized)	Center	n/a	1,400	1,400	1,028
Directional Horn (Maximum Safety)	Center	n/a	1,400	1,400	1,028
Directional Horn (Maximum Noise Reduction)	Center	n/a	1,275	210	0

3.3 Performance Specification

Acoustical specifications for the optimized train horn are presented below, including recommendations for the audible warning signal, the amplitude and frequency response of the optimized horn. The variable directivity of the horn was previously presented in Section 3.2.2.

3.3.1 Signal

The optimized horn has been specified to generate a signal with the same primary tones and harmonics (multiples of these primary tones) as a standard horn system. Standard horn systems typically include three or five horns (chimes) configured with either all the horns aimed in the same direction or with some of the horns directed forward and some directed backwards (bi-directional). Horns generally include either a 255 or 311 Hz tone as the lowest frequency.

For three-chime horns, the highest primary tone is often at 440, 480, or 494 Hz. For five-chime horns, the highest primary tone is often 554 or 622 Hz. Harmonics extend the overall frequency content of horns to 2,000 Hz and higher.

For the purposes of this study, the optimized horn has the same signal as a Nathan K-5-LA horn with primary tones at 311, 370, 415, 494, and 622 Hz (D#4, F#4, G#4, B4 and D#5) and their harmonics. A-weighted 1/3-octave band and narrowband spectra of the Nathan K-5-LA horn are shown in Figure 8. The primary tones are shown in the narrowband spectrum. This figure shows that the highest 1/3-octave band level is at 2,000 Hz and that levels at frequencies between 300 and 5,000 Hz are within 10 dBs of this maximum and significantly contribute to the overall level.

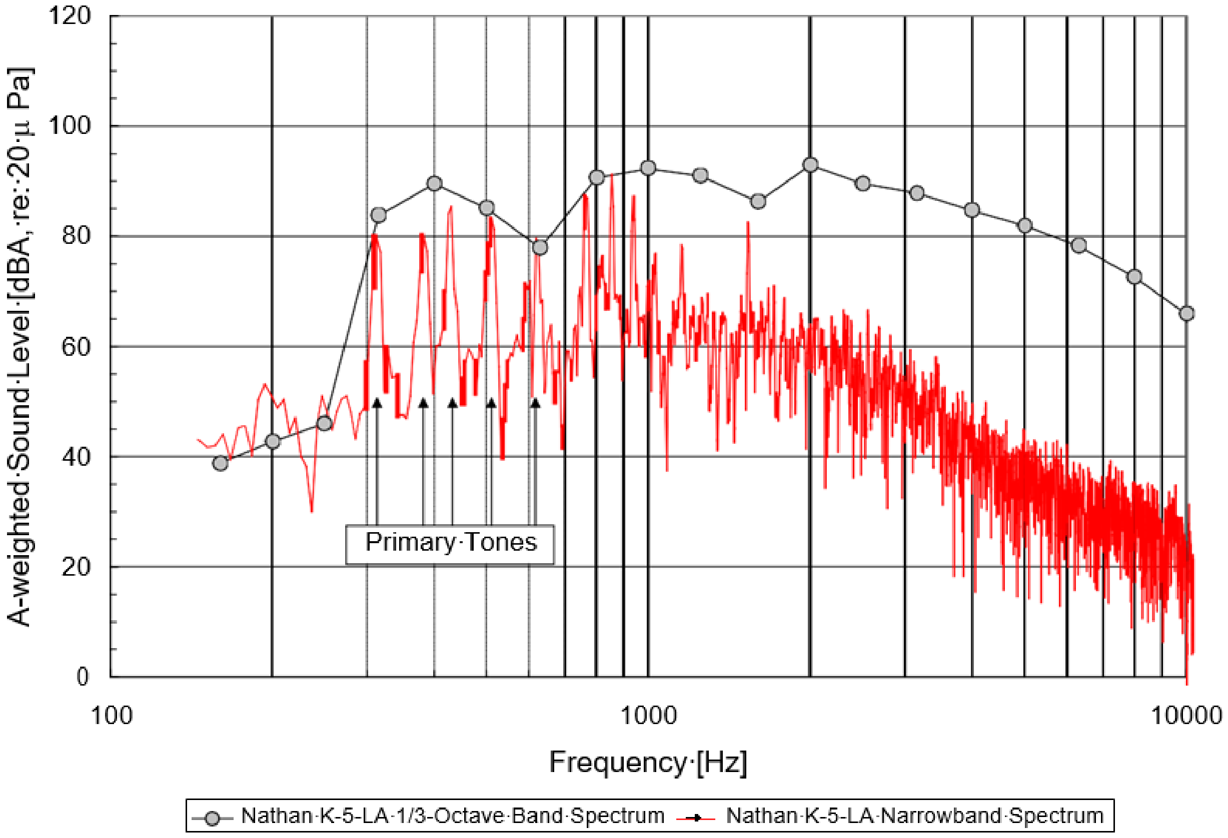


Figure 8. Recommended Optimized Train Horn Audible Signal

While studies have shown that signals with varying frequency or amplitude may improve the detectability or "sense of urgency" of a signal, a significant change to the audible signal would likely increase annoyance to abutters [32] [33]. With a signal that sweeps in frequency, such as ambulance sirens, it is more difficult to determine whether a source is approaching or departing compared to a constant tone where the Doppler Effect causes a simpler frequency shift. An additional reason to maintain an existing sound signature is that a new audible warning signal may reduce the association of the signal to a train event and potentially decrease safety. An optimized horn should also have a secondary emergency warning signal, such as a high-frequency series of tones, to provide an additional safety measure to avoid collisions.

The optimized horn would be sounded in the same sequence required for standard horns. Typically, horns are sounded using a long-long-short-long sequence that lasts for 15 to 20 seconds, with a maximum of 25 seconds, and continues until the first locomotive is entirely through the crossing. The actual sounding pattern will vary considerably according to train speed. For example, at 20 mph, a typical horn sounding may begin when the locomotive is 590 feet from the crossing with a 5-second "long" sounding, followed by a 1-second pause, another 5 second "long" sounding, another 1-second pause, a 2-second "short" sounding, a 1-second pause and finally a 7.7 second "long" sounding. The total time of the horn sounding would be 22.7 seconds. For a train at 60 mph, a typical horn sound may begin when the locomotive is 1/4-mile (1,320 feet) from the crossing with a 4-second "long" sounding, a 1-second pause, another 4-second "long" sounding, another 1-second pause and finally a 5.9-second "long" sounding. The total horn sounding time for a train at 60 mph is assumed to last 15.9 seconds.

3.3.2 Amplitude

The amplitude of the optimized horn's main beam is 110 dBA at 100 feet forward of the locomotive, the maximum allowable according to Title 49 Code of Federal Regulations (CFR) Parts 222–Use of Locomotive Horns at Public Highway-Rail Grade Crossings, and 229–Railroad Locomotive Safety Standards [14] [15], when the lead locomotive is between 1/4-mile and approximately 1/8-mile from the crossing to maximize detectability for motorists. At 1/8 mile from the crossing, the optimized horn generates a signal 3 dBs above the level considered to provide a 95% Likelihood of Noticeability at a passive grade crossing. Within 1/8 mile of the crossing, the amplitude is gradually decreased as the train reaches the crossing to maintain a signal 3 dBs above the level providing a 95% Likelihood of Noticeability. The minimum amplitude of the optimized horn main lobe is 104.6 dBA at 100 feet forward of the locomotive which is within the allowable range of the FRA Final Rule (96 to 110 dBA).

To achieve the required directivity of the optimized horn, it is possible that the device may propagate sound in a non-spherical spreading manner. For example, some high-powered acoustic hailing devices generate a coherent plane wave of sound, which is essentially an acoustic near field, for long distances. Under these propagation conditions, the drop-off with distance is less than with spherical spreading. Although technologies for the optimized train horn are expected to exhibit spherical spreading, it is best to specify the required amplitude output of the source at a distance of 100 to 150 feet. Often the power output or amplitude generated speakers is specified at a distance of one meter. Assuming a device propagates sound with spherical spreading, it should generate a sustainable (average) sound pressure level of 145 dBA or more at 1 meter to achieve a level of 110 dBA at a distance of 130 feet (i.e., 100 feet forward of the locomotive for center-mounted horns).

3.3.3 Frequency Response

The optimized train horn device must have a frequency response sufficient to generate sound within the frequency range of 250 to 10,000 Hz to replicate the primary tones and harmonics of the K-5-LA horn. The frequency response need not be linear within this frequency range; however, it must be sufficient to generate the required amplitudes according to frequency. The mid-frequency response (between 1,000 and 2,500 Hz) should be relatively flat and have sufficient power available to generate the overall A-weighted noise levels specified in Section 3.3.2. The low frequency (i.e., 250 to 1,000 Hz) response required depends significantly on the low-frequency directivity that can be achieved. Because it is very difficult to generate directional low-frequency sound, the low-frequency signal may need to be reduced to achieve the desired overall A-weighted directivity described below in Section 3.2.2. Therefore, at low frequencies, the optimized train horn device can likely have less available power than in the mid-frequency range. At high frequencies, between 2,500 and 10,000 Hz, the frequency response of the optimized device can have less available power than in the mid-frequency range since the required amplitudes in the high frequency range are 5 to 20 dBs lower than at mid-frequencies.

3.4 Directional Acoustic Source Technologies

This section presents brief descriptions of different technologies that can achieve some degree of acoustic directivity. The feasibility of each of these technologies to approach or meet the recommended specifications of the optimized horn is assessed.

3.4.1 Horns

There are several horn designs that are intended to control directivity [34]. Typically, when used as loudspeakers, the goal is to have equal directivity across all frequencies so that there is a similar sound field in all areas around the horn. One directional design is the multi-cellular horn where there are several acoustic elements. Most directional horns, such as radial horns, reversed flare horns, CE horns, and Manta-Ray horns are based on particular geometries of individual horns. Some horns can be relatively directional, especially at high frequencies; however, low frequency directivity is difficult to achieve and single-cell horns cannot vary the directivity as needed with the optimized horn.

3.4.2 Enclosures

An enclosure surrounding a horn or other acoustic source could direct the sound forward of the enclosure. However, an enclosure is not likely capable of providing significant directivity to the low-frequency or mid-frequency emissions and it would be difficult to vary the directivity pattern. For an enclosure to achieve variable directivity, it would need to slide forward and backward over the horn or possibly change shape. A wider beam of sound could be generated when the enclosure was partially covering the horn and a narrower beam could be generated when the enclosure more fully covers the horn and absorbs the sound energy radiating wayside and rear of the horn.

3.4.3 Phased Array

Individual acoustic elements or transducers are considered “simple” sources when they generate an omni-directional sound field. A phased array is a grouping of acoustic elements specific distances apart from each other so that they interact with each other and change the overall emission characteristics. Instead of generating an omni-directional sound field, the elements can cause constructive and destructive interference in particular directions and at particular frequencies. The resulting sound field can be highly-directional. In a phased array, the signal of each element is changed slightly (i.e., delayed in time) to cause these interactions and focus the total sound field specific directions. In a phased array, the radiation pattern typically has a main lobe and one or more sets of side lobes.

3.4.4 Ultrasound

Ultrasound is sound in the frequency range above human hearing (i.e., greater than 20 kHz). Beams of audible sound can be formed by producing a series of ultrasonic sound waves with slightly different frequencies which destructively interfere so the resultant beam is within the audible frequency range [35]. For example, ultrasonic beams at 60 and 61 kHz can destructively interfere and result in an audible 1 kHz signal. Because the high-frequency ultrasound is highly directional, the resulting audible signal is highly directional. Typically, this technology is used for interior spaces such as museums where sound from displays are needed, but only in small areas. This technology uses ultrasonic transducers which generate relatively low levels of acoustic power. Therefore, ultrasonically-formed beams of sound would not easily be capable of generating the significant amplitude required for a train audible warning device.

3.4.5 Acoustic Hailing Devices

AHDs are a type of phased array with a relatively large number of transducers. Some AHDs use piezoelectric transducers which use electrical energy to change the shape of the acoustic elements to radiate sound. AHDs are generally used in military applications to send high amplitudes of sound in a narrow beam. Audible signals can be voice commands or ear-piercing tones intended to debilitate others. AHD manufacturers include Ultra Electronics, LRAD Corporation, Conquest Innovations, LLC, MOOG, Inc., and IML Corporation, LLC.

Existing AHDs can generate a high amplitude of sound in a beam width of 30 degrees at frequencies of 1,000 Hz and higher which is narrower than that required for the optimized horn [36]–[40]. At lower frequencies, however, existing AHDs may only generate a beam width as narrow as 75 degrees which exceeds the specification of 42 degrees. The rear radiation of existing devices is typically 25 dBs lower than the main lobe at frequencies of 2,000 Hz and above. At lower frequencies, the emissions are less directional and more sound is radiated rear of the device (e.g., 15-dB reduction at 1,000 Hz and 5-dB reduction at 500 Hz). The size of the device is the main factor controlling the directivity at low frequencies. Since existing train horn signals have significant low frequency content (i.e., below 1,000 Hz), the directivity of AHDs in this low frequency region will be an important design issue.

Some representative specifications of AHDs include:

- Ultra Electronics HS-16™ can generate a sound pressure level of 148 dBA at 1 meter with a beam width (3 dB down) of 20 degrees (+/- 10 degrees) at 2 kHz [36].
- Long Range Acoustical Device Corporation 300X™ can generate a sound pressure level of 143 dBA at 1 meter with a beam width (3 dB down) of 20 degrees (+/- 15 degrees) at 1 kHz [37].
- Conquest Innovations MAX-4™ can generate a sound pressure level of 145 dB at 1 meter with a beam width of 30 degrees (+/- 15 degrees) over voice frequency band [38].
- MOOG RAHD-2™ can generate a high amplitude sound (80 dBA at 3 kHz at distances greater than 500 m) with a beam width of 30 degrees (+/- 15 degrees) at 2.75 kHz [39].
- IML Corporation SoundCommander® SC3600 can generate a directional sound field with a sound pressure level of 147 dB at 1 meter within a frequency range between 400 and 6,500 Hz [40].

The preferred application of AHDs to meet the optimized specification would be to electronically steer the beam (i.e., widen the main lobe) by changing the phase of some of the acoustic elements. Ultra Electronics has suggested that a curved linear array could be used to electronically steer a beam between the desired directivities [15]. Such an AHD would take approximately 200 ms or less to change its directivity pattern which would provide a suitable sweep over the course of the typical 15 to 20 second sounding event. Another potential application of AHDs to meet the optimized train horn specification could be to install three or more sources which are mechanically steered to fan out the sound as the train approaches the crossing; however, this would likely be more expensive.

3.5 Feasibility of Existing Technologies Meeting Acoustic Specification

The optimized train horn must provide a variable beam of sound forward of the locomotive while minimizing the side and rear radiation. Greater reduction of the side and rear radiation would provide greater environmental benefit. The optimized train horn assumes that the side and rear radiation can be reduced significantly even at low frequencies. It is critical that the optimized horn have a variable rather than static directivity. If a horn with a static directivity sufficient to protect motorists and pedestrian (198 degrees) were used in lieu of a variable directivity which narrows the beam to 42 degrees, the impact area would only be reduced 15 percent as discussed in Section 4.3. Therefore, while technologies such as horns, enclosures, and standard phased arrays could improve environmental noise conditions, the use of AHDs with variable directionality are likely necessary to provide significant improvement in the environmental noise conditions.

Depending on the directivity that can be achieved at low frequencies, it may be necessary to reduce the amplitude of the low frequency tones (i.e., 500 Hz and below) in the audible signal. It is expected that reducing some of the low frequency tones up to 10 dBs would not significantly change the character of the horn sound signature, the recognition that the audible warning signal is that of a train or the detectability of the horn.

4. Potential Environmental Noise Impact Benefit

A directional train horn has the potential to focus audible warning signals to desired locations including pedestrians and motorists at highway-rail grade crossings and workers and trespassers on the railroad right-of-way while minimizing unwanted sound, noise, to abutters in the community and railroad employees in the locomotive cab. This section describes the modeling approach and results to quantify the environmental noise exposure of a typical standard horn, the optimized horn, the modified horn, the horn with variable directivity maximized for safety and the horn with variable directivity maximized for noise benefit.

4.1 Environmental Noise Impact Criterion

Environmental noise impact from railroad sources is typically assessed based on the day-night noise level, or Ldn, at residential receptors and other locations where people sleep. Ldn is a noise metric which includes noise over a 24-hour long period with a 10-dB penalty applied to sound that occurs during the nighttime period of 10PM to 7AM. This metric takes into account the amplitude, duration, daily frequency and timing of noise events.

Noise impact criteria for railroad projects are defined by the Federal Transit Administration and FRA based on a comparison of the existing noise levels to the future noise levels with the project [41] [42]. The Federal Aviation Administration and the U.S. Department of Housing and Urban Development have set a noise standard for the acceptability of exterior Ldn of 65 dBA [43]. For the purpose of this study, noise impact has been defined as the area where horns alone generate levels equal to or greater than Ldn of 65 dBA. Since computation of the Ldn depends on the number and timing of events, a typical grade-crossing with one train pass-by every hour (i.e., daytime and nighttime) has been assumed. Impact areas have been modeled for train pass-bys occurring only in one direction and train pass-bys occurring in both directions on double track with 15 feet track separation.

4.2 Environmental Noise Modeling Methodology

Environmental noise impact contours have been modeled using Soundplan™, commercially-available sound propagation software, with the Nordic General Prediction Model propagation algorithms. The model assumes the surrounding terrain is soft flat ground and no adjustments for acoustic shielding from building rows and trees or refraction from wind gradients (i.e., from the atmosphere or from the moving train) have been included. Environmental noise exposure has been modeled for a right-angle crossing with the aforementioned train operations with trains traveling at 20, 40, and 60 mph. As discussed in Section 3.3.1, the sounding patterns of these different train speeds vary considerably both in regard to location along the track and total sounding duration.

4.3 Environmental Noise Modeling Results

The Ldn noise contours for a train pass-bys in one direction at 60 mph with a standard Nathan K-5-LA horn mounted in the center of the long hood of a GP40 locomotive is shown in Figure 9.

The noise contours in this figure have a shape similar to the static directivity of this standard horn mounted in the center of the locomotive where the noise levels are reduced forward and rear of the locomotive due to acoustic shielding. Figure 10 shows the Ldn noise contours for pass-bys in one direction with the optimized horn. This figure shows that the optimized train horn generates narrower noise contours near the 1/4-mile marker when the horn begins sounding and the narrowest directivity is needed. As the train approaches the crossing and the beam width of the optimized horn must widen, the noise contours expand. In fact, most of the environmental noise exposure with the optimized horn occurs on the side of the grade crossing beyond the roadway.

Figure 11 and Figure 12 show the noise impact areas for the standard and optimized train horns for a train speed of 60 mph with pass-bys in both directions. Comparatively, these figures show that the area of noise impact is significantly greater for the standard horn. The standard horn generates a "butterfly" like pattern where the large lobes on the opposite side of the grade crossing from the train's direction of travel are a result of the directivity pattern which is affected by shielding from the locomotive body. The noise contour of the optimized horn is narrower near the 1/4 and 1/8-mile markers, where the device has a highly directional pattern, and then the noise contour increases closer to the grade crossing.

As described in Section 4.1, noise impact areas defined by Ldn of 65 dBA are based on train activity of one train per hour. If there is less train activity, the Ldn 65 dBA impact area would be smaller as shown by the noise contours greater than 65 dBA in the existing figures. If there were greater train activity, the Ldn 65 dBA impact area would be larger as shown by the noise contours less than 65 dBA on the existing figures.

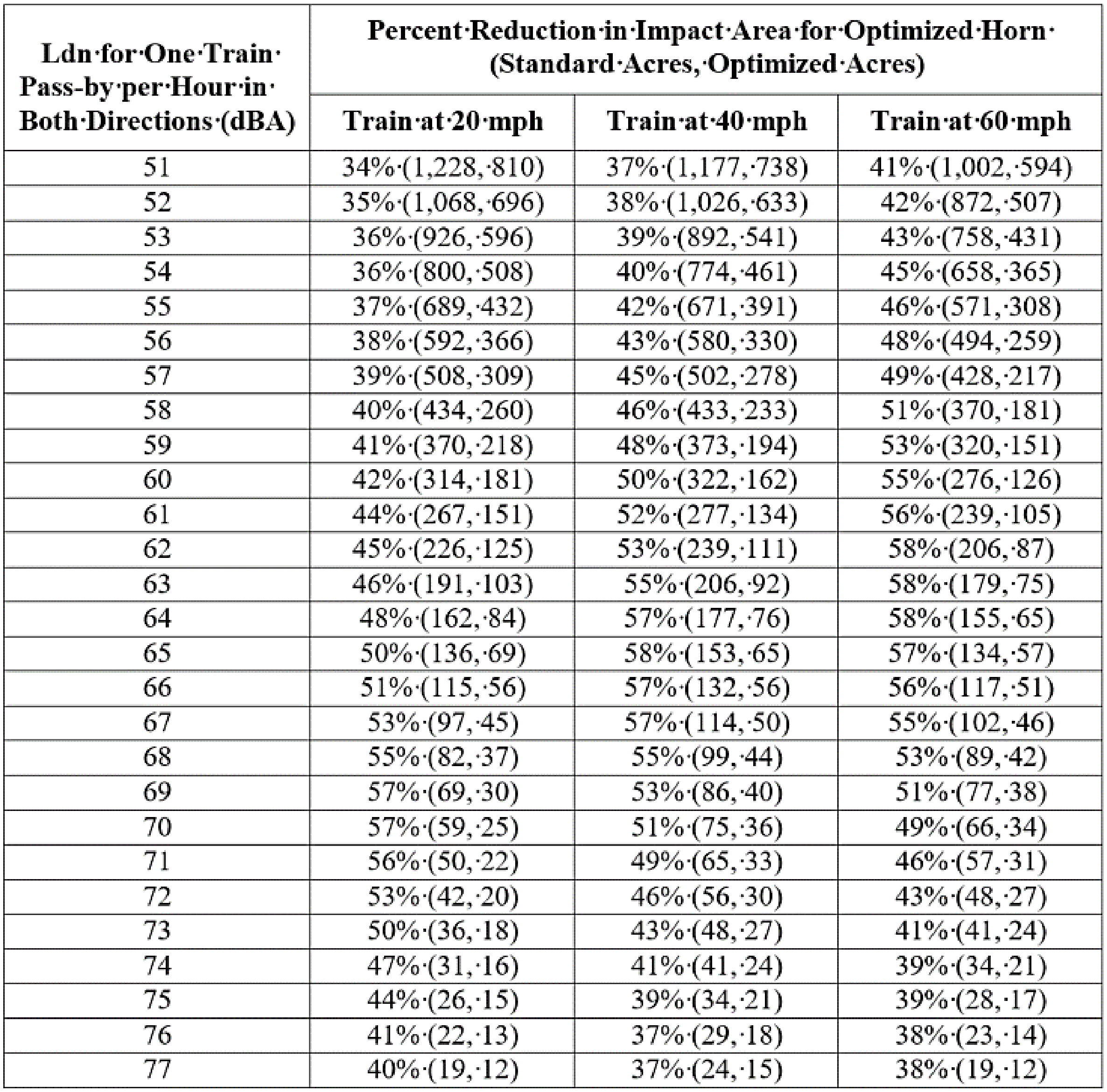
Figure 13 shows the noise impact areas corresponding to Ldn 65 dBA for all the horns:

- This figure shows how the modified horn reduces noise impact only by a small amount near the beginning of the sounding event. The modified horn produces an impact area of 114 acres representing only a 15 percent reduction compared to the standard horn.
- For the directional horn maximized for safety, the impact area is 83 acres representing a 38 percent reduction compared to the standard horn.
- The optimized train horn generates a significantly smaller area of noise impact than the standard horn. In particular, noise impact is considerably reduced 1/4-mile from the crossing where the optimized horn can maintain a narrow beam width. The area of impact is 134 acres with the standard horn versus 57 acres for the optimized horn (including railroad right of way). Therefore, the area of potential noise impact is reduced 57 percent with the optimized horn. Generally, the optimized horn reduces Ldn by 4 to 15 dBs depending on receptor location. The wayside distance from the tracks to noise impact is generally reduced to 120 feet from 700 feet at locations 1/4-mile from the crossing, reduced to 500 feet from 1,100 feet 1/8-mile from the crossing and reduced to 800 feet from 1,200 feet near the crossing.
- The impact area for the directional horn with minimum amplitude to maximize noise reduction is 11 acres representing a 91 percent reduction, albeit with a significant reduction in detectability. This contour is so close to the train that the individual contributions from each part of the sounding pattern can be seen.

Table 2 presents a summary of the percent reduction in the impact area and the total number of impacted acres for the standard and optimized horns for Ldn values between 51 and 77 dBA. This table shows that the percent reduction in impact area ranges from 34 to 58 percent with less reduction provided for slower train speeds. This is due to the fact that at low train speeds a locomotive engineer must sound its horn over a shorter length to not exceed the 20 second sounding limit and the sounding pattern typically begins closer to the crossing with a wider horn angle. Interestingly, because of the low train speed, a longer sounding duration is assumed than for higher train speeds (i.e., 22.7 seconds at 20 mph versus 15.9 seconds at 60 mph). So, the total area of impact at 20 mph is actually slightly higher than at 60 mph.

Table 3 presents a summary of the noise impact areas for all horn analyzed based on trains traveling at 60 mph with typical activity (i.e., one train per hour). One observation is that the optimized on-board locomotive train horn is not expected to reduce noise more than wayside horns, particularly directional wayside horns which could focus sound almost entirely to areas where safety is of concern along roads and sidewalks and away from abutters.

Table 2. Summary of Environmental Noise Impact Benefit of Optimized Horn



Ldn for One Train Pass-by per Hour in Both Directions (dBA)	Percent Reduction in Impact Area for Optimized Horn (Standard Acres, Optimized Acres)		
	Train at 20 mph	Train at 40 mph	Train at 60 mph
51	34% (1,228, 810)	37% (1,177, 738)	41% (1,002, 594)
52	35% (1,068, 696)	38% (1,026, 633)	42% (872, 507)
53	36% (926, 596)	39% (892, 541)	43% (758, 431)
54	36% (800, 508)	40% (774, 461)	45% (658, 365)
55	37% (689, 432)	42% (671, 391)	46% (571, 308)
56	38% (592, 366)	43% (580, 330)	48% (494, 259)
57	39% (508, 309)	45% (502, 278)	49% (428, 217)
58	40% (434, 260)	46% (433, 233)	51% (370, 181)
59	41% (370, 218)	48% (373, 194)	53% (320, 151)
60	42% (314, 181)	50% (322, 162)	55% (276, 126)
61	44% (267, 151)	52% (277, 134)	56% (239, 105)
62	45% (226, 125)	53% (239, 111)	58% (206, 87)
63	46% (191, 103)	55% (206, 92)	58% (179, 75)
64	48% (162, 84)	57% (177, 76)	58% (155, 65)
65	50% (136, 69)	58% (153, 65)	57% (134, 57)
66	51% (115, 56)	57% (132, 56)	56% (117, 51)
67	53% (97, 45)	57% (114, 50)	55% (102, 46)
68	55% (82, 37)	55% (99, 44)	53% (89, 42)
69	57% (69, 30)	53% (86, 40)	51% (77, 38)
70	57% (59, 25)	51% (75, 36)	49% (66, 34)
71	56% (50, 22)	49% (65, 33)	46% (57, 31)
72	53% (42, 20)	46% (56, 30)	43% (48, 27)
73	50% (36, 18)	43% (48, 27)	41% (41, 24)
74	47% (31, 16)	41% (41, 24)	39% (34, 21)
75	44% (26, 15)	39% (34, 21)	39% (28, 17)
76	41% (22, 13)	37% (29, 18)	38% (23, 14)
77	40% (19, 12)	37% (24, 15)	38% (19, 12)

Table 3. Summary of Environmental Noise Impact for All Horns and Trains at 60 mph

Horn	Noise Impact Area (Acres)	Reduction in Noise Impact Area (Relative to Standard Horn)
Standard Horn (Typical)	134	--
Modified Horn (Static Directivity)	114	15%
Directional Horn (Optimized)	83	38%
Directional Horn (Maximum Safety)	57	57%
Directional Horn (Maximum Noise Reduction)	11	91%

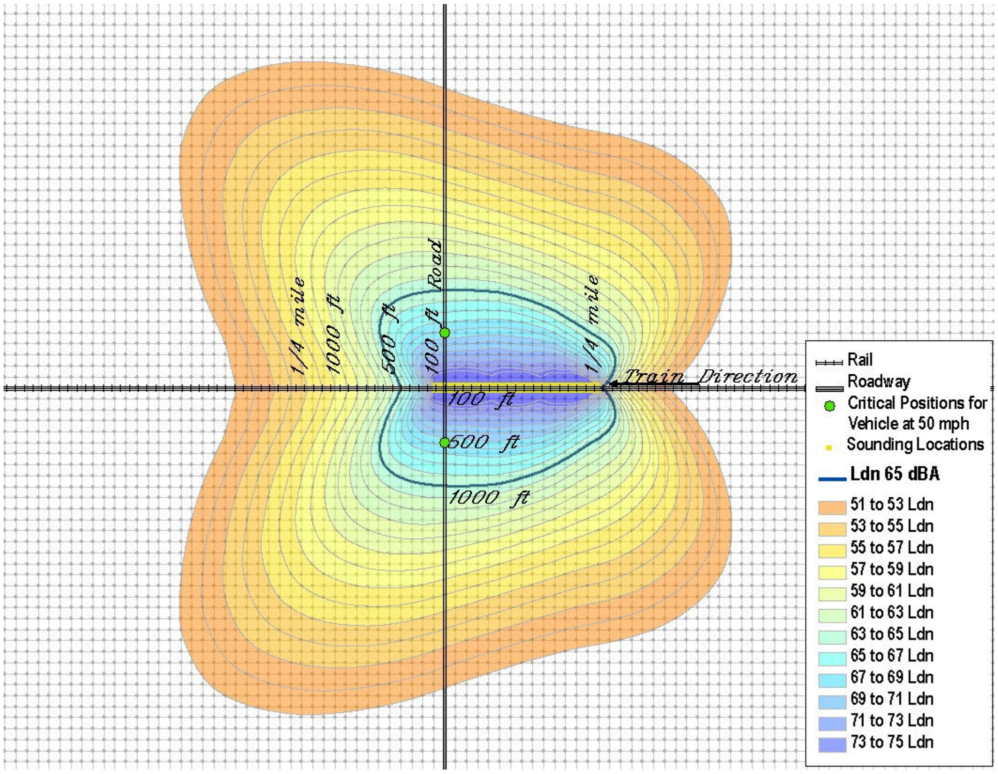


Figure 9. Ldn Noise Contours for Standard Horn, Pass-bys in One Direction at 60 mph

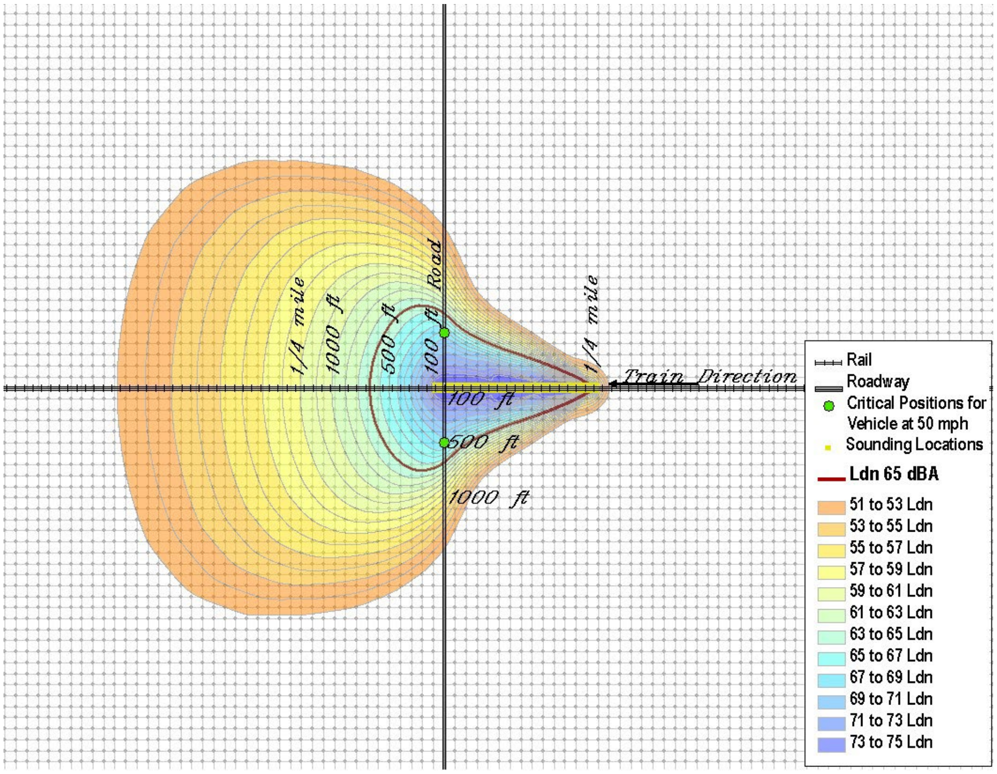


Figure 10. Ldn Noise Contours for Optimized Horn, Pass-bys in One Direction at 60 mph

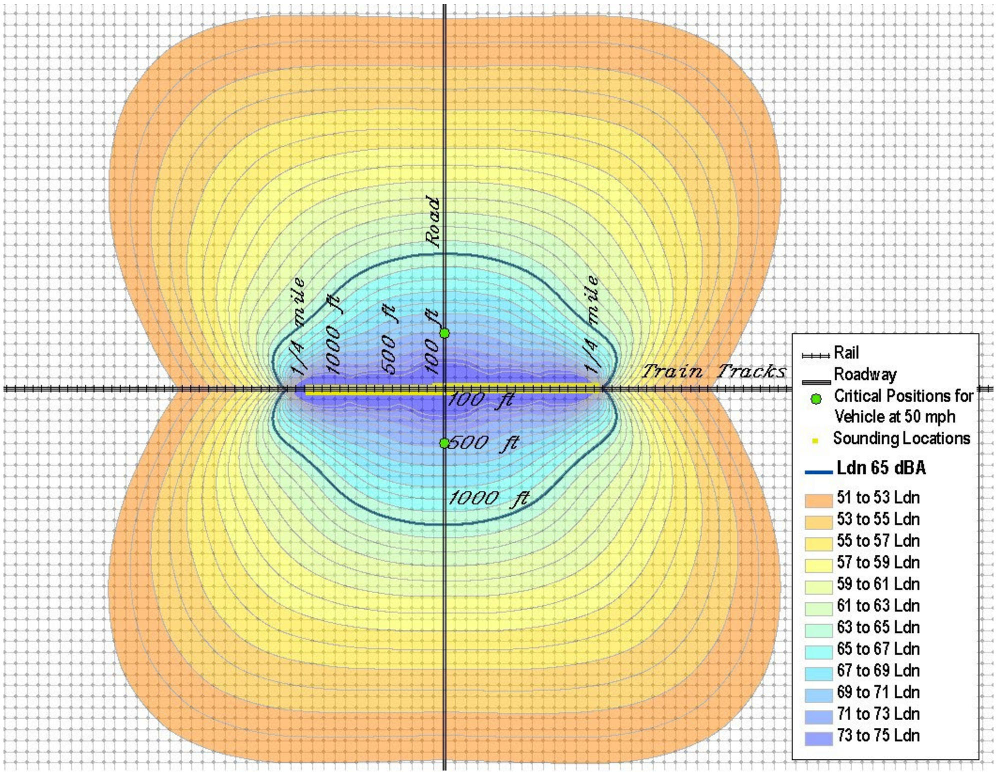


Figure 11. Ldn Noise Contours for Standard Horn, Pass-bys in Both Directions at 60 mph

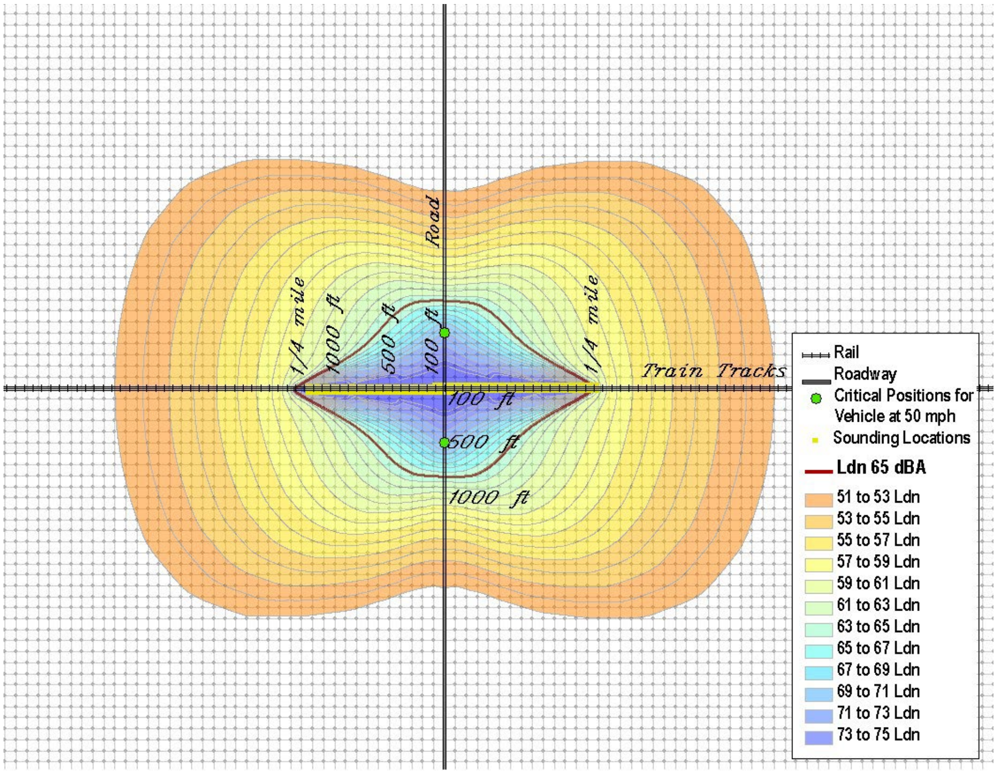


Figure 12. Ldn Noise Contours for Optimized Horn, Pass-bys in Both Directions at 60 mph

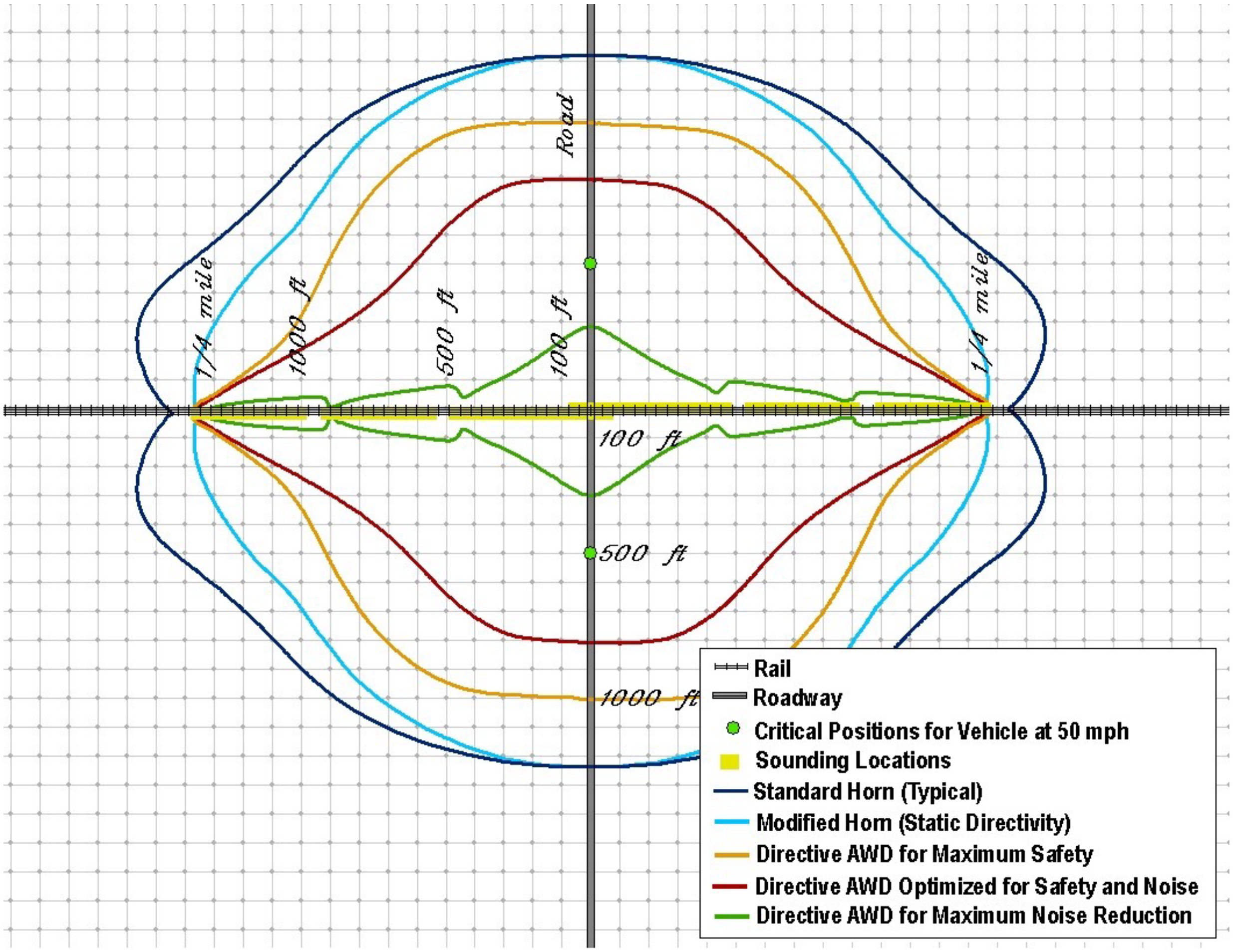


Figure 13. Noise Impact Areas for Standard, Modified and Directional Horns

5. Potential Occupational Noise Exposure Benefit

While the optimized train horn recommended in this study is designed primarily to minimize environmental noise impact and maintain or improve detectability for safety, there is the potential that a new horn design could improve in-cab noise levels and reduce occupational noise exposure. This section describes the methodology used to assess in-cab noise levels and the comparative results between standard horns and the optimized horn.

5.1 Occupational Noise Exposure Criterion

FRA regulates in-cab noise levels to the equivalent of an 8-hour time-weighted average (TWA) of 90 dBA [19]. Occupational noise exposure can also be referenced to a "noise dose" where a dose of 100 percent is equivalent to a TWA noise level of 90 dBA.

5.2 Occupational Noise Exposure Modeling Methodology

In-cab noise levels for standard horns and the optimized horn have been modeled for different mounting locations and three different train speeds (20, 40, and 60 mph). In-cab noise levels are a function of many factors, such as horn mounting location, horizontal and vertical directivity patterns of the horn, structure-borne noise, potential air gaps or open windows and the noise reduction properties of the different cab materials. Since the purpose of this analysis is to compare in-cab noise levels between standard horns and the optimized horn, most of these factors would be the same for any of the devices. The most significant factors that may affect interior noise levels are the amplitude and the directivity. The modeling uses a simple approach which compares the cumulative amplitude in particular directions for each horn as follows:

- For horns mounted on the cab roof with windows closed, it has been assumed that noise from all directions will equally enter the cab through airborne or structure-borne noise paths. Therefore, the interior noise levels are a function of the entire 360-degree radiation pattern.
- For cab roof-mounted horns with windows open, the interior noise levels have been assumed to be a function of the horn's 360-degree radiation with a 3 dB greater contribution of noise applied to two 90-degree angles (i.e., 45 to 135 degrees and 225 to 315 degrees) to the sides of the horn.
- For horns mounted in the center of the long hood with windows open or closed, the interior noise levels have been assumed to be a function of the forward-facing 45-degree angle (-22.5 to +22.5 degrees).

Studies of standard horn systems have shown that maximum in-cab noise levels average 95.7 dBA for cab roof installations with windows closed, 100.9 dBA for cab roof installations with windows open, 84.5 dBA for center-mounted horns with windows closed and 97.5 dBA for center-mounted horns with windows open [6] [13]. In this analysis, the cumulative energy radiated by the standard horns (i.e., the average of all horns) has been adjusted to match these measured results. These same adjustments were then applied to the optimized horn. This approach provides results, in terms of the overall increase or decrease in in-cab noise levels for the optimized horn as well as the absolute noise levels. The absolute noise levels allow us to determine the noise dose (i.e., percentage of the 8-hour TWA noise allowed) that a single horn blowing sequence would cause.

This methodology assumes that the majority of noise enters the cab through airborne paths and does not factor in differences in structure-borne noise paths. This approach also does not consider variation in vertical directivity between the standard and optimized horns. While this is a relatively simple approach to assessing interior noise levels, without a more complex ray tracing or finite element model of the horns and the locomotive, the results provide a general indication of the potential benefit that an optimized horn could provide.

5.3 Occupational Noise Exposure Results

A time history of the in-cab noise levels has been computed based on the modeling approach described in Section 5.2. For the standard horns, the in-cab noise levels are constant since the amplitude of these horns does not change. Since the optimized train horn varies in amplitude and directivity, the in-cab noise levels change according to train location. Figure 14 shows a time history of in-cab noise levels for a train at 60 mph for a standard horn and the optimized horn mounted on the cab roof (windows closed) and center-mounted. This figure demonstrates the following:

- For cab-roof mounted horns, the optimized horn generates levels that are 1 to 4 dBs below the standard horns. Near the 1/4-mile position, the optimized horn is focusing sound forward and less noise enters the cab through the side and rear paths. As the train reaches the 1/8-mile location, the optimized horn has widened out and increased interior noise levels; however, levels are still lower than the standard horn. Starting at 1/8-mile, the optimized horn gradually reduces its amplitude and the in-cab levels begin to decrease again even though the beam continues to widen.
- For the center-mounted horn, the optimized horn generates in-cab levels approximately 1 dB higher than standard horns near the 1/4-mile position. This is because the optimized horn is specified to have the maximum allowable sound level 110 dBA at 100 feet forward of the locomotive. Even at its narrowest, the optimized horn generates a beam wide enough to cover the cab area similar to standard horns. So, there is no benefit in the reduced directivity. At 1/8-mile the optimized horn gradually decrease its amplitude which reduces in-cab level up to 4 dBs below standard horn levels. The noise dose, which takes into account the total noise exposure, however, is slightly higher for the optimized horn than for the standard horn.

The total noise dose for a single horn-blowing sequence ranges between 0.0056 and 0.4193 percent for standard horns depending on train speed and mounting locations. For the optimized horn, the noise dose ranges between 0.0209 and 0.2186 percent. On average, there is a 31.2 percent reduction in the noise dose for horns mounted on the cab roof with windows closed, there is a 32.0 percent reduction for horns mounted on the cab roof with windows open and there is a 6.8 percent increase in noise dose for horns mounted in the center of the long hood (windows open or closed). These noise doses are very low and show how horn noise is not generally a concern for occupational noise exposure. For example, if a horn sounding event at a grade crossing created a 0.5 percent noise dose, a locomotive engineer would need to go through 200 crossings for horn blowing to exceed the allowable limits.

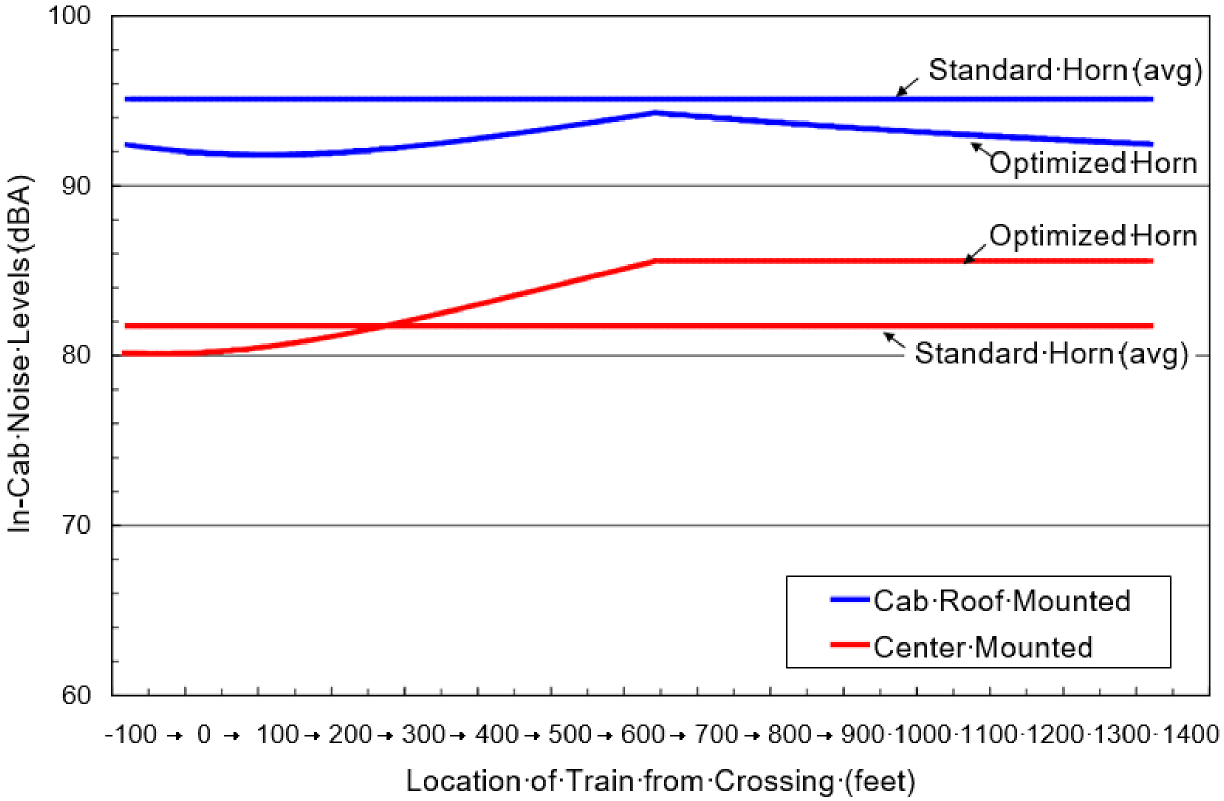


Figure 14. In-Cab Noise Level Time Histories for Standard and Optimized Horns

It should be noted that moving a horn from the cab roof to the center of the long hood has been shown to reduce in-cab noise levels between 3 and 11 dBA [13]. Replacing a cab roof-mounted horn with an optimized horn would be expected to reduce in-cab noise levels 1 to 4 dBs. A greater reduction to in-cab noise levels may be possible if the horn were to be mounted more forward of the cab to benefit from the reduced wayside and rear emissions.

6. Cost and Implementation Concerns

6.1 Cost

The cost of standard horn systems is approximately $1,000. The costs of existing AHDs such as the Ultra Electronics HS-16 and LRAD Corporation 500x, which would generate sufficient amplitude and static directivity as narrow as 30 degrees, are approximately $7,000 to $8,000. The desired solution would be to modify an existing AHD to generate the variable directivity as described. The cost of such an AHD has been estimated to be similar or slightly higher than existing AHDs with a potential for significantly lower costs with large volume production. These costs could be compared to the cost of other noise mitigation measures used for horn noise such as wayside horns and building sound insulation improvements. The cost of building sound insulation improvements (i.e., new windows and doors) is typically $25,000 per residence. The cost of wayside horns is often $50,000 or more per grade crossing. When assessing the cost-effectiveness of different technologies, the added benefit of allowing voice commands as well as emergency warning tones to be generated with these devices should also be considered. The ability to provide verbal instructions would improve the safety of workers or pedestrians in the railroad right-of-way.

6.2 Reliability

AHDs are typically used in military applications and therefore they meet extensive military specifications for exposure to hazards such as temperature, humidity and shock, and are expected to be well-suited for railroad applications. Being a relatively modern piece of technology, the security of these units on locomotives should be considered. The size of AHDs is an important design factor which governs the amplitude available and the directionality limitations at low frequencies. The actual size limitations of an optimized train horn, especially in regard to the height above the locomotive, need to be defined.

6.3 Implementation

The optimized horn control system requires information on the train position relative to the crossing. This could be obtained most easily from the train speed and a defined sounding duration (i.e., 15 to 20 seconds). The amplitude and directivity of the optimized horn would be controlled within the circuitry of the acoustic device depending on train position. Train speed can be obtained from an on-board GPS or the speedometer. The sounding pattern can be controlled manually by the train engineer with typical long-long-short-long signaling or an automated signaling sequence could be played based on the train speed.

As a safety precaution, it would be beneficial to include a directivity override that would automatically widen the directivity pattern to properly protect motorists and pedestrians if the horn sounding was initiated too late or for non-standard train movements such as in rail yard facilities.

7. Conclusions and Recommendations

QinetiQ North America, Inc. designed a train horn to optimize low frequency directivity, with potential modifications to reduce the low-frequency horn signal and electronically-steer the beam width as a function of train position or speed, is considered to be a feasible technology to meet the specified goals.

Table 4 summarizes the specifications and performances of standard and the optimized horns.

Table 4. Summary of Standard and Optimized Horn Specifications and Performances

Specification	Standard Horns	Optimized Horn	Comment
Audible Signal	Five-chime	Five-Chime	Low-frequency amplitudes may be decreased with optimized horn
Amplitude	96 to 110 dBA at 100 feet forward of locomotive	110 to 104.6 dBA at 100 feet forward of locomotive	Higher amplitudes will provide greater safety to motorists and pedestrians
Directivity	Omni-directional	Variable directivity	Optimized to minimize environmental noise impact and maintain safety
Frequency Response	250 to 10,000 Hz	250 to 10,000 Hz	Low frequency directivity is important design issue.
Distance Horn Audible	1,400 feet (average)	1,400 feet	Inside vehicle traveling at 50 mph at critical distance from crossing. Longer distance provides greater safety
Distance Horn Noticeable	1,263 feet (average)	1,400 feet	Inside vehicle traveling at 50 mph at critical distance from crossing. Longer distance provides greater safety
Distance Horn 95% Likelihood of Noticeability	533 feet (average)	1,028 feet	Inside vehicle traveling at 50 mph at critical distance from crossing. Longer distance provides greater safety
Environmental Impact Area (Ldn 65 dBA)	134 acres	57 acres	For one train per hour, pass-bys in both directions at 60 mph. A 57% reduction in area.

Specification	Standard Horns	Optimized Horn	Comment
Occupational Noise Exposure	0.0056 to 0.4193% noise dose per crossing	0.0209 to 0.2186% noise dose per crossing	31 to 32% reduction in noise dose for cab roof mounted horns. No significant benefit for center-mounted horns
Cost	$1,000	$7,000 to $8,000	Potential for significant cost reductions of optimized horn with large volume production.

Additional horn design options were examined to determine the range of performance a directional train horn could provide. These included a "modified" horn, which has a static directivity pattern sufficient to direct sound to the widest critical angle required, a horn with variable directivity and amplitude maximized for safety and a horn with variable directivity and amplitude minimized for noise impact reduction.

- For a train horn with the same dynamic directivity as the optimized horn, but with constant amplitude of 110 dBA, the detectability is maximized. The signal would be audible and noticeable for the entire sounding event (1,400 feet) and 95 percent likely to be noticeable for 1,028 feet. The noise impact area is reduced to 38 percent for this design compared to standard horns.
- For a train horn with the same dynamic directivity as the optimized horn, but with constant amplitude of 96 dBA, the noise benefit is maximized. The signal would be audible for 1,275 feet over the sounding event, noticeable for 210 feet, but does not reach a detectability level above the threshold for 95% Likelihood of Noticeability. The noise impact area is reduced by 91 percent with this design compared, albeit with a significant reduction in detectability.
- For a modified horn with static directivity, the distances of detectability are the same as the optimized horn since it is assumed to maintain the same signal and amplitude to the critical position of the vehicle and then reduce emissions at wider angles. The noise impact area is reduced only by 15 percent with this design compared to standard horns. This design demonstrates the need for variable directivity to obtain substantial noise reduction.

To further assess the feasibility of this technological application and quantify the environmental benefit, it is necessary to conduct further research. Recommendations for further research include:

- Working with AHD manufacturers, develop a prototype horn approaching or meeting the optimized horn specification.
    - Refine an appropriate audible signal similar to standard horns including potential low-frequency amplitude reductions
    - Conduct static and dynamic performance measurements of best-available technology approaching or meeting optimized horn specification

  - Model the environmental noise benefit based on performance measurements and refined audible signal.
- Research an appropriate emergency signal and recommend an acoustical specification.

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Appendix A.
Detectability Time Histories of Standard Horns

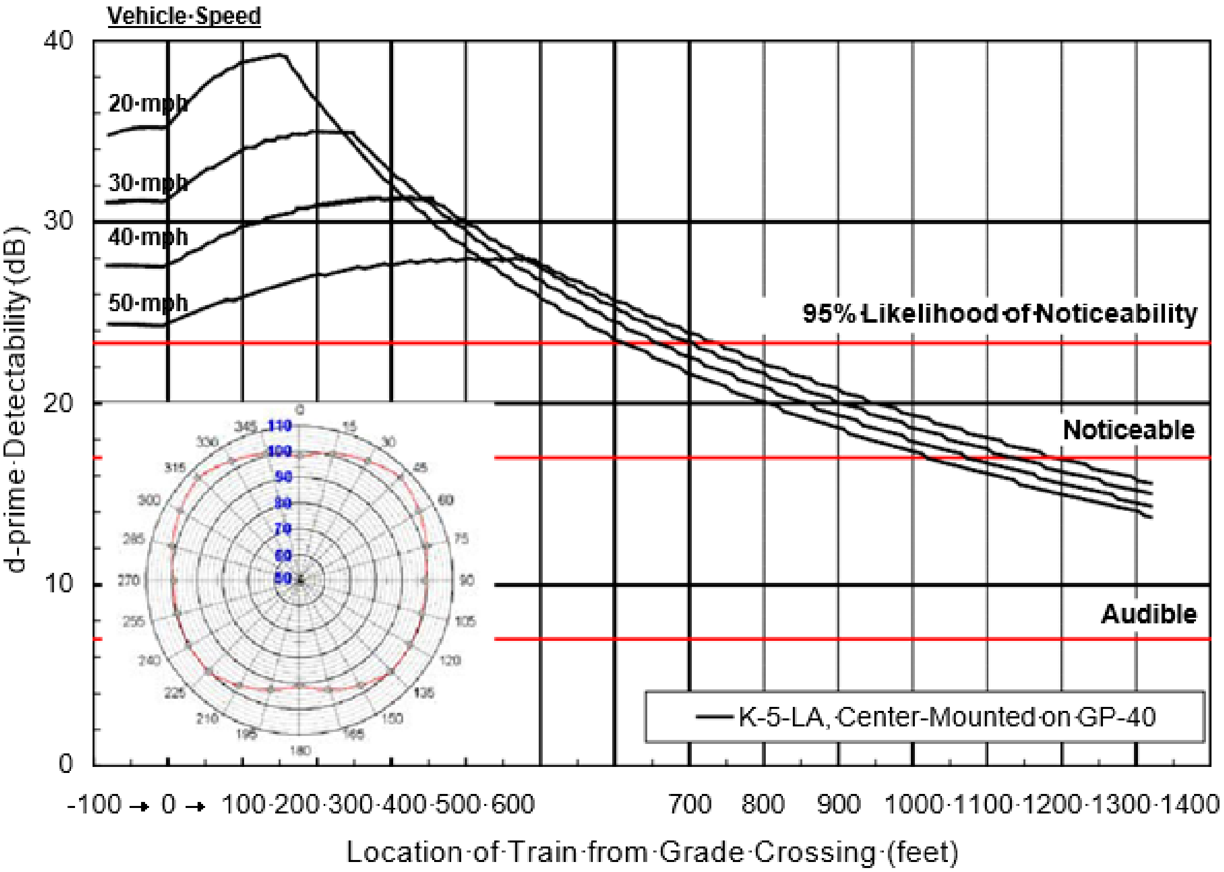

Figure A1. Detectability and Directivity of K-5-LA Horn Center-Mounted on GP-40

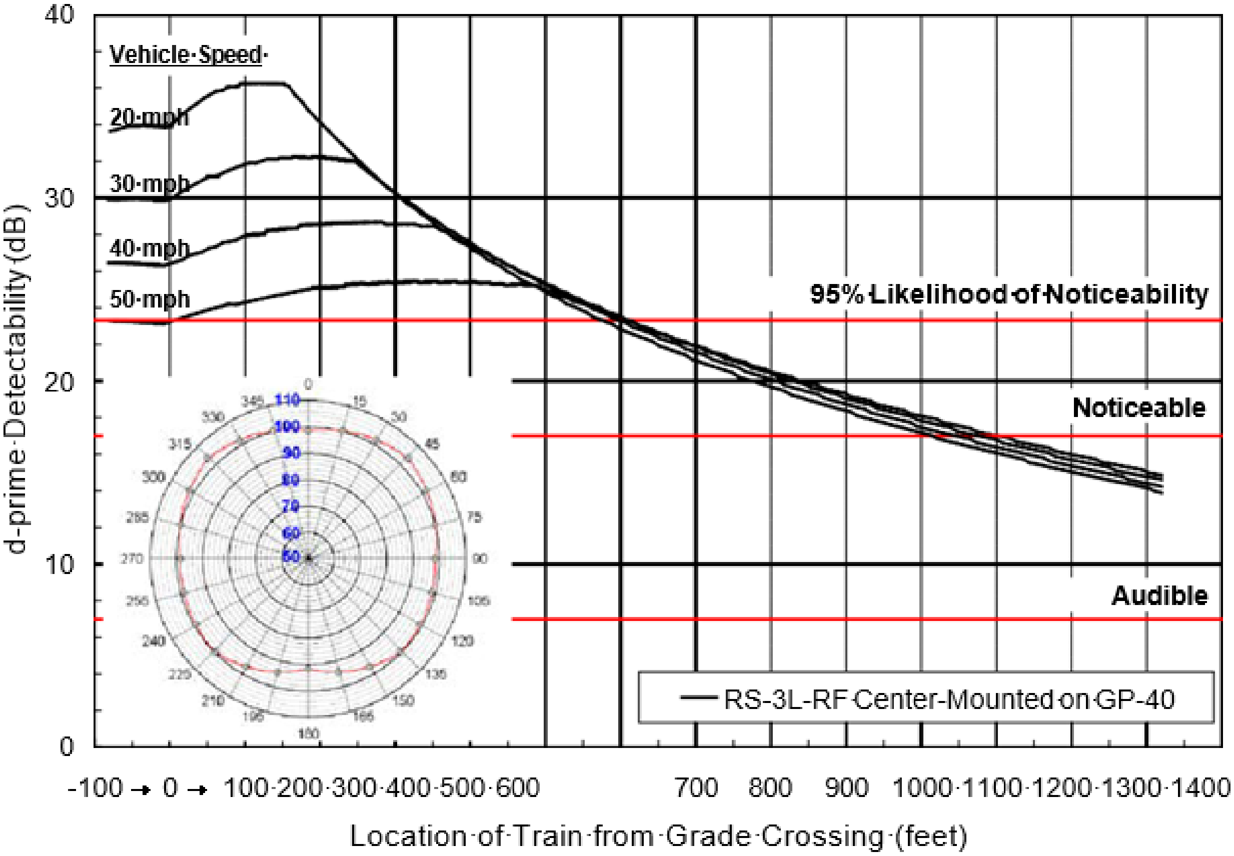

Figure A2. Detectability and Directivity of RS-3L-RF Horn Center-Mounted on GP-40

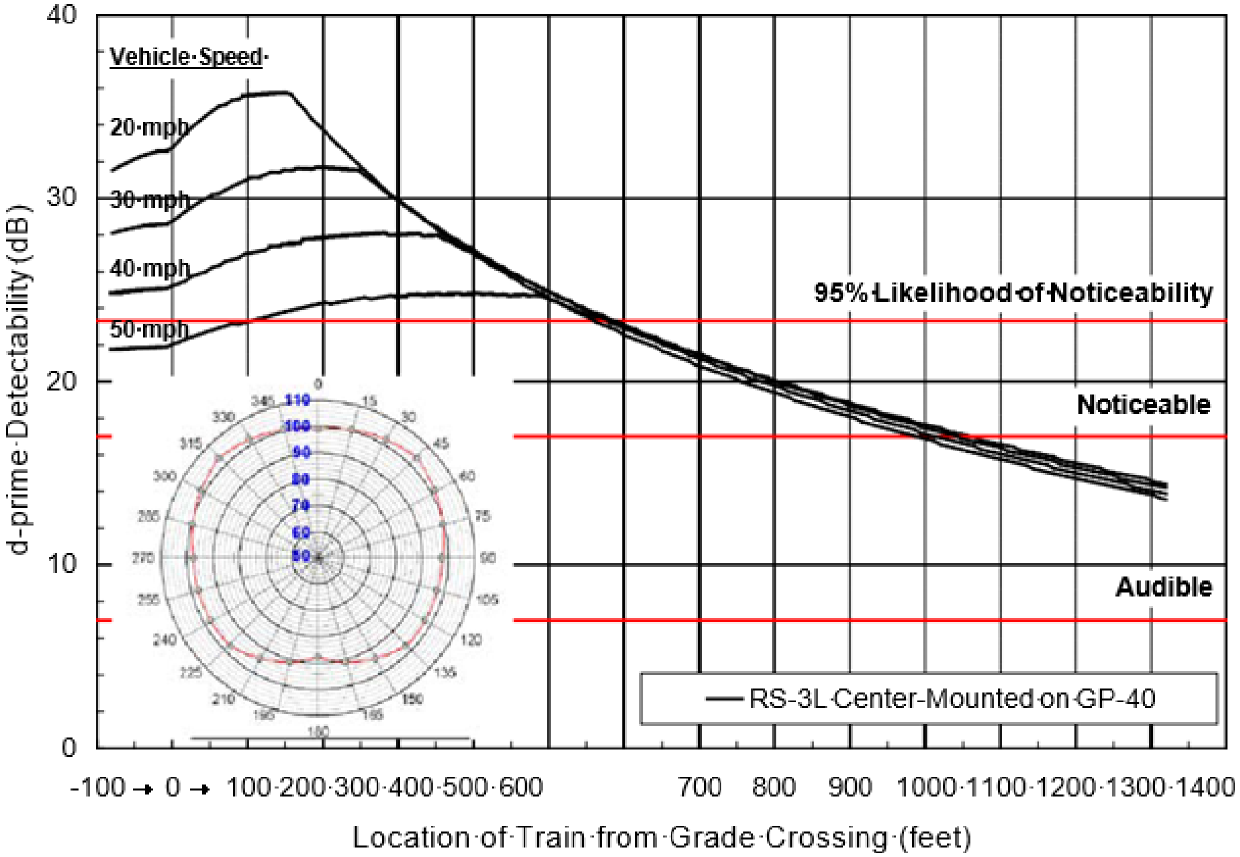

Figure A3. Detectability and Directivity of RS-3L Horn Center-Mounted on GP-40

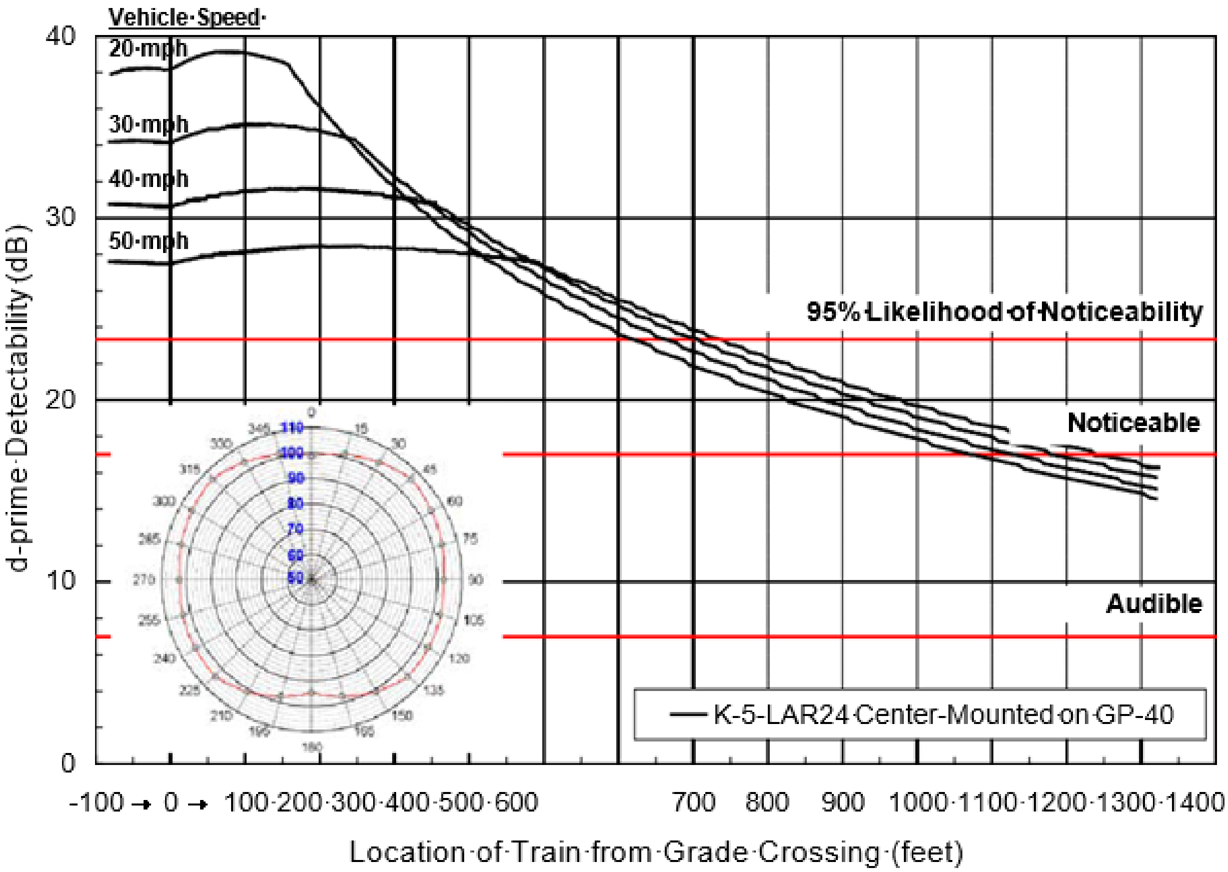

Figure A4. Detectability and Directivity of K-5-LAR24 Horn Center-Mounted on GP-40

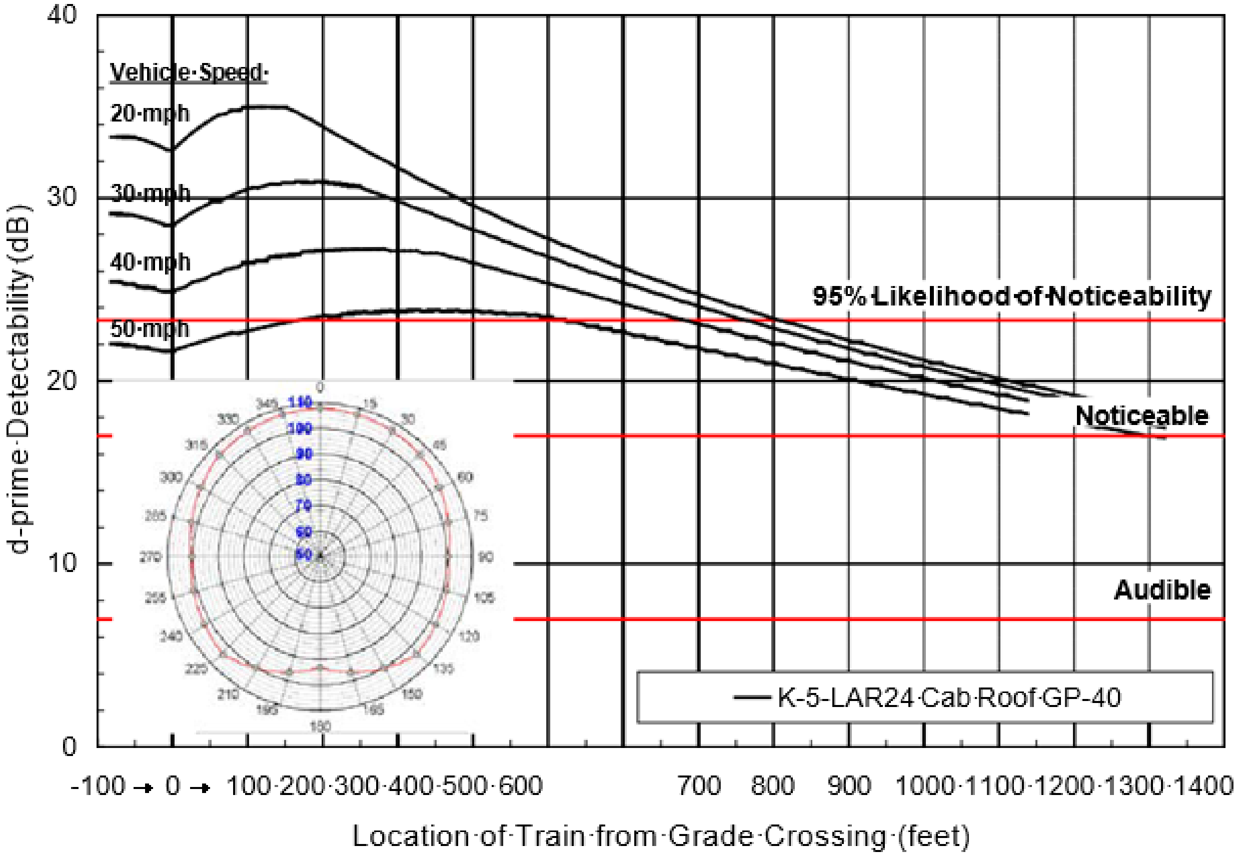

Figure A5. Detectability and Directivity of K-5-LAR24 Horn Mounted on Cab Roof of GP-40

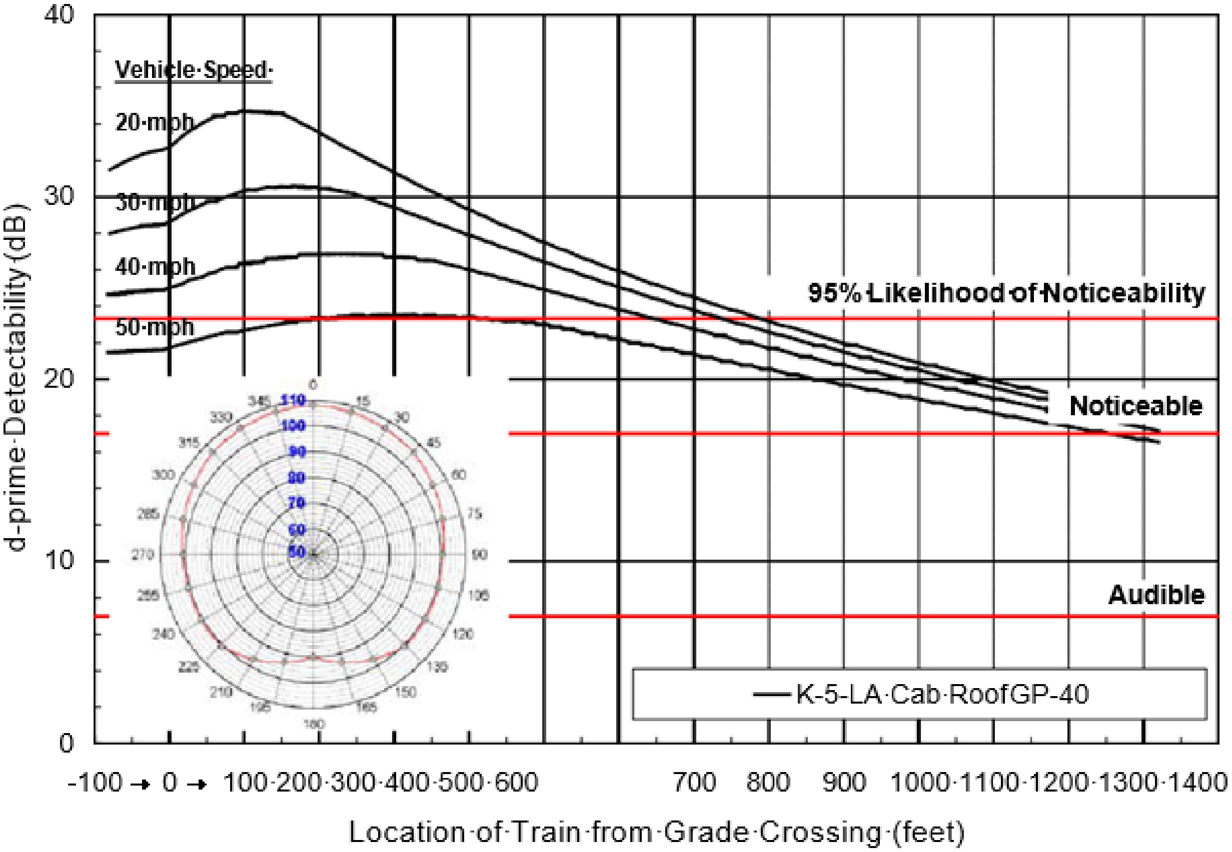

Figure A6. Detectability and Directivity of K-5-LA Horn Mounted on Cab Roof of GP-40

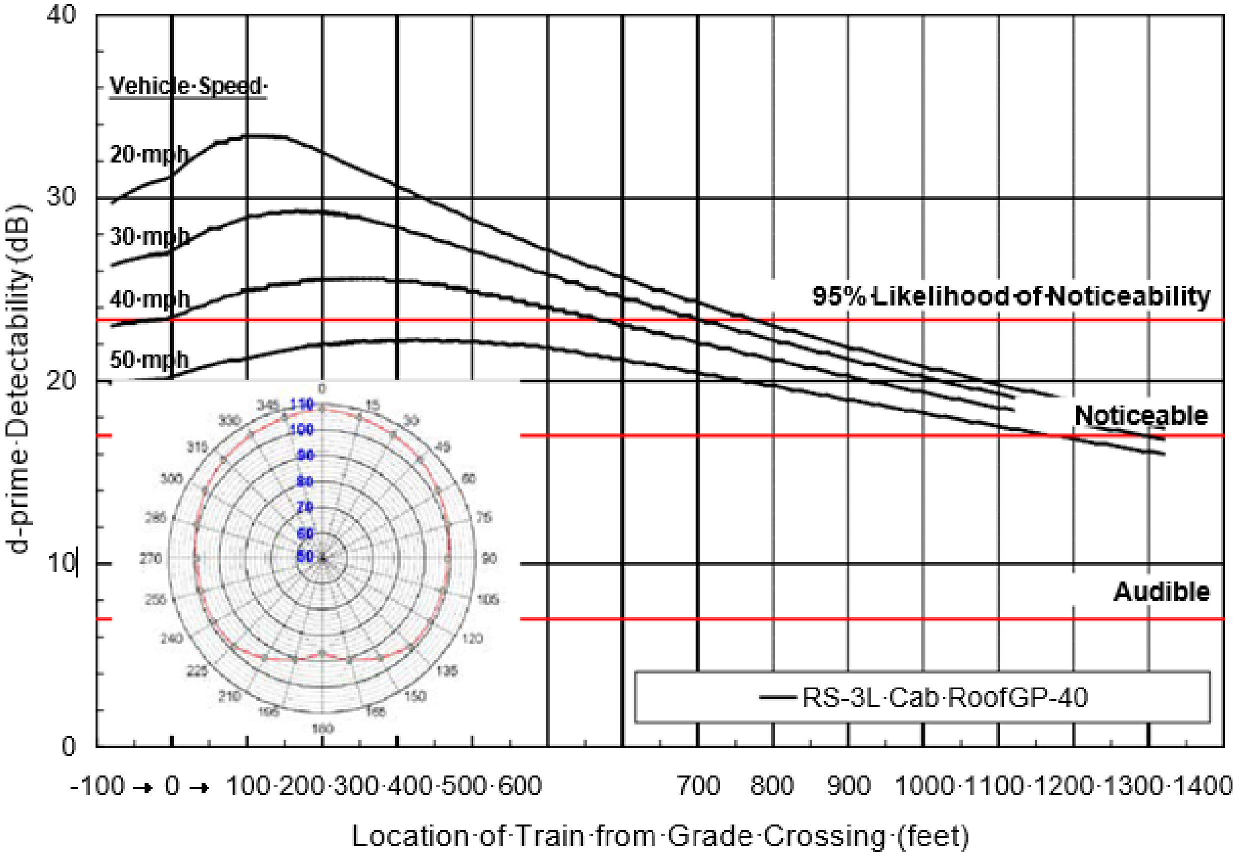

Figure A7. Detectability and Directivity of RS-3L Horn Mounted on Cab Roof of GP-40

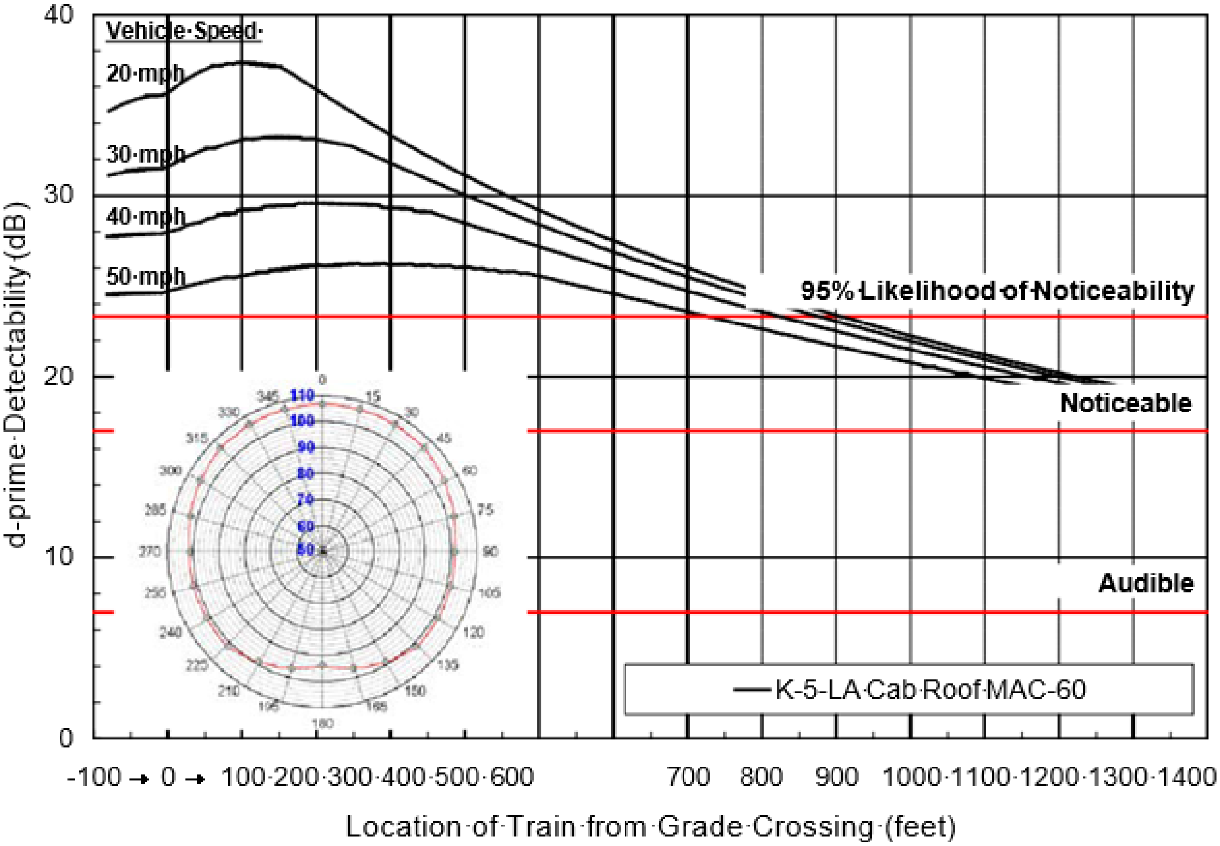

Figure A8. Detectability and Directivity of K-5-LA Horn Mounted on Cab Roof of MAC-60

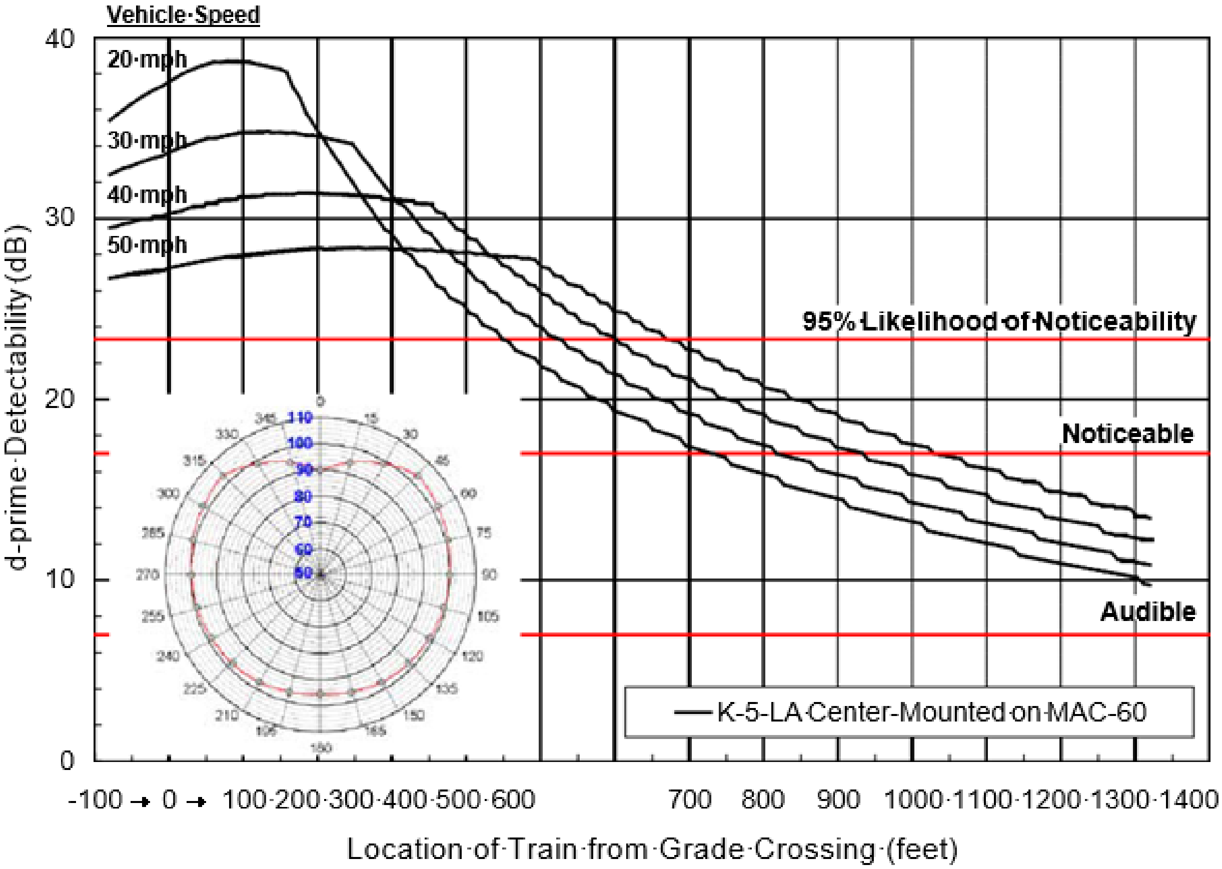

Figure A9. Detectability and Directivity of K-5-LA Horn Center-Mounted on MAC-60

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AHD	Acoustic Hailing Device
dBA	A-weighted Sound Decibel
Ldn	Day-night Sound Level
CFR	Code of Federal Regulations
CTZ	Critical Track Zone
FRA	Federal Railroad Administration
Hz	Hertz
ISO	International Standards Organization
MTA	Los Angeles County Metropolitan Transit Authority
SAE	Society of Automotive Engineers
dB	Sound Decibel (Referenced to 20 micro-Pascals)
TWA	Time-weighted Average
Volpe	Volpe National Transportation Systems Center