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Locomotive Horn Detectability at Closely-Spaced Highway-Rail Grade Crossings

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14. ABSTRACT
Researchers assessed the feasibility of altering the locomotive horn sounding pattern of repetition at each crossing in a series of closely-spaced grade crossings by exploring the specific geometries and warning requirements for motorists in advance of such crossings. Acoustic modeling on five example scenarios showed that the locomotive horn would meet the auditory detection criteria out to a minimum of 1200 ft downstream of the primary crossing in those scenarios. The results from this analysis confirm that further exploration is needed on this topic, including assessing the feasibility and effectiveness for both detectability and driver response, to only sounding the locomotive horn prior to arriving at the first in a series of closely-spaced grade crossings.

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Highway-rail, grade crossing, locomotive horn, train horn, safety, quiet zone, railroad

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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)

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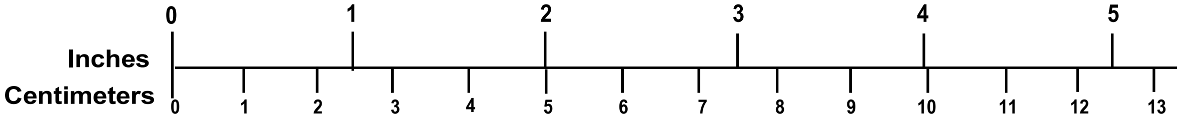
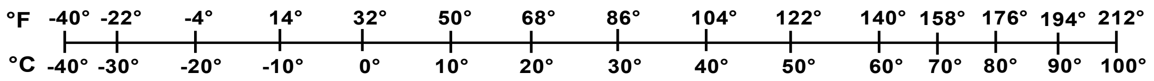


QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



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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Cover photo is of a satellite view of three closely spaced crossings in Plant City, Florida. (Source: ESRI)

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Executive Summary

The John A. Volpe National Transportation Systems Center (Volpe) was tasked by the Federal Railroad Administration (FRA) Office of Research, Development, and Technology to explore the feasibility of altering the locomotive horn sounding pattern of repetition on approach to closely-spaced grade crossings. FRA 49 CFR Parts 222 and 229 *Final Rule - Use of Locomotive Horns at Highway-Rail Grade Crossings, 2006* [1], commonly known as the "horn rule," requires the use of locomotive horns at public highway-rail grade crossings. At closely-spaced crossings, where two or more crossings are spaced less than one-quarter mile apart, the standardized pattern is generally not feasible; the resulting effect could be a near-continuous sounding of the horn and disruption to nearby residences and businesses.

From July 2021 to October 2022, researchers investigated horn detectability by drivers in specific scenarios of interest involving closely-spaced grade crossings. Each involved open/public at-grade crossings located on railroad main lines outside of quiet zones. Researchers used the FRA Grade Crossing Inventory System (GCIS) database [8] and the Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD) to document the number and characteristics of these crossings in the US. The analysis identified 361 rail segments with three or more public at-grade crossings not in quiet zones within 300 ft of each other (representing 1,349 grade crossings). Researchers then studied the characteristics of these crossings, such as number of trains per day, warning device types, maximum timetable speed, roadway speed limit, roadway classification, and land use. These characteristics were used to define specific scenarios of interest for acoustics modeling and analysis using a source-path-receiver framework. Scenario parameters involved grade crossing geometry and characteristics, driver behavior considerations, and acoustics elements.

The research team performed acoustic modeling using the Advanced Acoustic Model (AAM), a suite of software tools that allows users to model vehicle sound levels and auditory detection metrics from any traditional or evolving transportation noise source. Acoustic modeling was limited to scenarios of interest, which were a priori understood by the research team to yield the most likely opportunities for further exploration. Five scenarios of interest were defined. All scenarios involved active grade crossings with spacing of 300 ft. The type of locomotive horn, train speed, and vehicle interior noise environment were the varying parameters across these scenarios.

The acoustic modeling analysis showed similar results for different locomotive horns and different train speeds in all five scenarios. Researchers determined that when sounded only on approach to the primary crossing, the locomotive horn would be detectable between 8 and 15 seconds for motorists stopped at the gates downstream of the primary crossing across the scenarios. Additionally, there would be a range of 4 to 10 seconds of delay between the last horn blast and when the train arrives at the downstream crossings. The team also showed that the locomotive horn would meet the auditory detection criteria out to a minimum of 1,200 ft downstream of the primary crossing in all scenarios.

The results from this analysis will guide further exploration of this topic, including assessing the feasibility and effectiveness of both detectability and driver response, to only sounding the locomotive horn prior to arriving at the first in a series of closely-spaced grade crossings.

1. Introduction

The John A. Volpe National Transportation Systems Center (Volpe) provides technical support to the Federal Railroad Administration (FRA) on all aspects of grade crossing safety and trespass prevention research. This support includes key research associated with all aspects of the railroad rights-of-way (ROWs), including highway-rail intersections and trespass issues.

Commonly known as the "horn rule," FRA 49 CFR Parts 222 and 229 *Final Rule - Use of Locomotive Horns at Highway-Rail Grade Crossings, 2006* [1] requires locomotive horns to be sounded at a level between 96 and 110 decibels A (dBA) at 100 ft forward of locomotive (+/- 20 degrees). The engineer must sound the horn for a minimum of 15 seconds and a maximum of 20 seconds, except if a train is traveling faster than 45 mph, in which case engineers do not have to sound the horn until it is within one-quarter mile of the crossing even if the advance warning is less than 15 seconds. Wherever feasible, horns should be sounded in the standardized long-long-short-long pattern. At closely-spaced crossings, where two or more crossings are spaced less than one-quarter mile apart, the standardized pattern is generally not feasible; the resulting effect could be a near-continuous sounding of the horn and disruption to nearby residences and businesses.

The research team explored locomotive horn sounding needs at closely-spaced grade crossings by analyzing the specific geometries and warning requirements for motorists in advance of such crossings. Ultimately, the team found that it may be feasible to sound the locomotive horn only on approach to the first (i.e., primary) crossing, eliminating repeated sounding for crossings in a closely-spaced group downstream of the primary crossing. The term "quasi-quiet zone" is used in this report to describe this type of sounding scenario, and the majority of the report focuses on defining a closely-spaced group, warning signal detection properties, and additional risk factors which may be encountered.

1.1 Background

Prior to setting the horn rule, research was conducted to derive the maximum sound level requirement within the rule [2], which was defined as the sound level at which there is a 95 percent likelihood that a person with normal hearing will hear (i.e., detect) and recognize an average locomotive horn at the instant in time at which detection must occur to avoid a collision.[1] Behind this sound level requirement is a signal detection analysis that combines information and data from several sources and technical models. The research performed in this study is based on this prior analysis framework, updated to reflect the current state-of-art acoustic source (i.e., locomotive horn) and motor vehicle characteristics, sound propagation models, and auditory detection models.

Data inputs and assumptions within a signal detection analysis include several factors, including grade crossing characteristics (e.g., advance warning, train/roadway speeds, and number of tracks), acoustic characteristics of the environment (e.g., warning signal characteristics and motor vehicle characteristics), and driver behavior and expectations. These factors will be discussed in further detail in Section 4, Section 5, and Section 6.

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[1] This is defined as a hypothetical locomotive horn based on the average acoustic characteristics of locomotive horns at the time the rule was put in place.

1.2 Objectives

The objective of this research was to determine the feasibility of altering the locomotive horn sounding pattern of repetition at closely-spaced grade crossings. The results from this analysis will guide further exploration of this topic, including assessing the feasibility and effectiveness (e.g., both detectability and driver response) of only sounding the locomotive horn prior to arriving at the first in a series of closely-spaced grade crossings.

1.3 Overall Approach

To determine the feasibility of altering the locomotive horn sounding pattern of repetition at closely-spaced crossings, researchers analyzed the FRA Grade Crossing Inventory System (GCIS) database to identify and characterize those crossings, defined specific scenarios of interest, and performed acoustic modeling on horn detectability.

1.4 Scope

Researchers investigated horn detectability by drivers in specific scenarios of interest involving closely-spaced crossings. This study was limited to acoustic modeling on a set of defined scenarios involving open/public at-grade crossings located on railroad main lines. Crossings in quiet zones were excluded from this study.

1.5 Organization of the Report

This report is organized as follows:

- Section 2 presents a review of the relevant literature.
- Section 3 presents an overview of grade crossing characteristics.
- Section 4 presents the acoustic modeling framework.
- Section 5 presents the acoustic modeling and results.
- Section 6 presents the human factors implications.
- Section 7 presents the conclusions and discussion of the study.
- Section 8 presents the limitations of the study.

2. Literature Review

FRA 49 CFR Parts 222 and 229 *Final Rule - Use of Locomotive Horns at Highway-Rail Grade Crossings, 2006* [1], commonly known as the "horn rule," requires the use of locomotive horns at public highway-rail grade crossings. The rule notes a few exceptions [1]:

- "A railroad operating over a public highway-rail grade crossing may, at its discretion, choose not to sound the locomotive horn if the locomotive speed is 15 miles per hour or less and the train crew or appropriately equipped flaggers provide warning to motorists."
- "…not required within highway-rail grade crossing corridors that are equipped with supplementary safety measures (SSMs) at each public highway-rail grade crossing."
- "…not required within highway-rail grade crossing corridors that have a Quiet Zone Risk Index at or below the Nationwide Significant Risk Threshold or the Risk Index With Horns."

The engineer must sound the horn for a minimum of 15 seconds and a maximum of 20 seconds, except if a train is traveling faster than 45 mph, in which case engineers do not have to sound the horn until it is within one-quarter mile of the crossing even if the advance warning is less than 15 seconds. The horn rule also regulates horn levels to between 96 and 110 dBA at 100 ft forward of the locomotive (i.e., +/- 20 degrees from the centerline of the track). Horns are typically sounded using a long-long-short-long pattern, as specified in the rule, but engineers may vary the pattern as necessary for crossings that are closely spaced and also in emergency situations. The term "closely" is used in the horn rule but is not defined. The Manual on Uniform Traffic Control Devices (MUTCD) uses the term but only quantifies it in relation to roadway interchanges, by providing guidance on when to use *Interchange Sequence* signs instead of *Advance Guide* signs if the distance between interchanges is less than 800 ft [3].

Noise pollution is a problem in communities across the United States. In a 2003 estimate by FRA, locomotive horns "sound at over 98 percent of public highway-rail crossings, and over 9 million Americans living and working along rail lines are incidentally exposed to the 'noise' from this source" [4]. The horn rule provides a way for communities to create "quiet zones" where the horn is not to be sounded in normal conditions. Typically, this involves a risk analysis and usually installation of additional safety improvements to the affected crossings to compensate for the loss of routine sounding of the horn [5].

One other approach to lessen the acoustic impact of horn sounding is to install wayside horns at gated crossings, which is allowed as a one-to-one substitute for the locomotive horn [1]. Wayside horns minimize the audible footprint in comparison to locomotive horns [5]. They have been shown to reduce noise to levels that are more acceptable to a community [6].

A novel approach recently researched by FRA focused on the feasibility of using a directive horn on the locomotive [7]. The idea is to direct the sound toward the upcoming crossing, thereby reducing the area of noise impact. The study found that "detectability could be improved and noise impact area reduced by 50 percent or more, depending on amplitude" [7]. This approach, however, needs further research before real-world implementation should be considered.

A review of locomotive horn acoustic modeling research is presented in Section 4. The research team has found no record of previously conducted research on specific geometries and warning requirements for motorists in advance of closely-spaced crossings.

3. Grade Crossing Characteristics

Prior to embarking on locomotive horn detection analysis, the research team first needed to explore and ‘bound’ the universe of closely-spaced crossings. The team needed to develop the specific scenarios of interest, and make sure they were representative of those encountered in real-world situations.

The research team asked several pertinent questions. What is a typical distance between crossings? How many crossings make up a group? Where are these crossings located and in what type of environment? What types of warning devices are typically at these crossings? What are typical roadway and train speeds?

The primary sources of data for the analysis of grade crossing characteristics were the FRA GCIS database [8] and the Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). FRA developed the GCIS database in 1970 and it is managed by the Office of Railroad Safety. It contains all U.S. public and private highway-rail grade crossings, with detailed information on individual crossings. This database was used to identify the locations and characteristics of closely-spaced crossings. The NTAD contains geographic datasets of transportation facilities, transportation networks, associated infrastructure, and other political and administrative entities. The research team used the North American Rail Network (NARN) shape file to identify crossings that are located on the same rail line.

3.1 Data Analysis Method

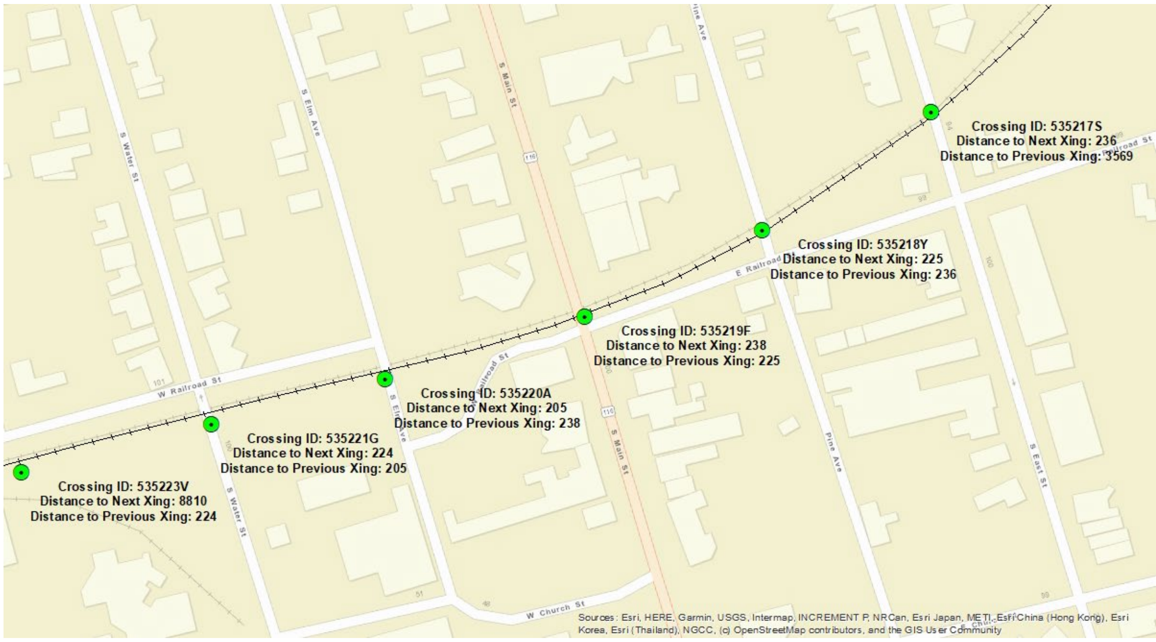
For this research, only open/public at-grade crossings located on railroad main lines and not in quiet zones were considered in the identification of closely-spaced crossings. As previously stated, the term “closely” is used in the horn rule but is not defined. For this research, the team defined closely-spaced crossings as crossings within one-quarter mile or less of each other on the same rail line. Table 1 shows the FRA GCIS data fields that were used to obtain this subset of crossings. Out of the total 436,163 grade crossings in the GCIS database, the filter criteria resulted in 107,871 public at-grade crossings.

Table 1. FRA GCIS Data Fields Used for the Consideration of Closely-Spaced Crossings

GCIS Data Field	Description	Data Field Entry
TypeXing	Crossing Type	= 3 - Public
PosXing	Crossing Position	= 1 - At Grade
ReasonID	Reason for Update	<> 16 - Closed
		<> 24 - No Train Traffic
Whistban	Quiet Zone	= 0 - No
MainTrk	Number of Main Tracks	>= 1

The 107,871 grade crossings were plotted along the North American Rail Network using ArcGIS software. Since the team was interested in crossings that are located on the same rail line, the NARN was divided into segments (i.e., railroad track between two junctions) and crossings were grouped based on whether they shared the same segment. The team identified 18,754 segments that range in length from 13 ft to 286.2 miles. Out of the 18,754 segments, 7,817 have at least one crossing; the number of crossings in each segment range from 1 to 228.

Crossings on each segment were spatially analyzed to calculate the distance to the nearest crossing on either side of each crossing. Figure 1 shows an example of the spatial analysis output for a group of six crossings that are within 300 ft of each other.



Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community

Figure 1. An Example of a Rail Segment with Crossings Within 300 ft of Each Other

3.2 Results

City blocks typically measure between 300 and 500 ft; therefore, the crossings were grouped based on their placement within 300 ft, 400 ft, or 500 ft of the immediately adjacent crossing along the same line.[2]

Table 2 shows the number of rail segments with closely-spaced crossings by 300 ft, 400 ft, and 500 ft tolerance. The 300 ft tolerance resulted in 361 rail segments with three or more crossings (totaling 1,349 crossings), the 400 ft tolerance resulted in 988 rail segments with three or more crossings (totaling 3,920 crossings), and the 500 ft tolerance resulted in 1,511 rail segments with three or more crossings (totaling 6,153 crossings). The number of crossings in a rail segment ranged from 3 to 18 for 300 ft and 400 ft tolerance and 3 to 22 for 500 ft tolerance.

Table 2. Number of Rail Segments with Closely-Spaced Crossings by Distance Tolerance

Number of Crossings Within Rail Segment	≤300 ft	≤400 ft	≤500 ft
3	249	580	848
4	53	195	320
5	26	90	136
6	14	50	76
7+	19	73	131
Total	361	988	1,511

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[2] Reference.com (2020). How Many Feet Are in a City Block? Accessed on September 20, 2022.

A crossing can either be equipped with active or passive warning devices. Active warning devices are those that provides roadway users a positive indication of incoming rail traffic. The *FRA Guide for Preparing U.S. DOT Crossing Inventory Forms* lists gates, flashing lights, highway traffic signals, wigwags, bells, or other activated and special active warning devices as *Active*.[3] The remaining warning devices, which includes stop signs, crossbucks, other signs or signals, and no signs or signal, are listed as *Passive*. Table 3 shows a breakdown of rail segments with closely-spaced crossings by warning device type for the 300, 400, and 500 ft spacing tolerances. A group of crossings is labeled *Active* if all the crossings in the rail segment are equipped with active warning devices, *Passive* if all the crossings in the rail segment are equipped with passive warning devices, and *Mixed* if there is a mix of active and passive crossings within the rail segment. As can be seen, most of the rail segments are *Mixed* crossing type, equipped with both active and passive warning devices. The number of rail segments in the *Active* category increases as the distance tolerance increases.

Table 3. Number of Rail Segments with Closely-Spaced Crossings by Warning Device Type

Number of Crossings Within Segment	**≤300 feet**			**≤400 feet**			**≤500 feet**		
	Active	Passive	Mixed	Active	Passive	Mixed	Active	Passive	Mixed
3	68	69	112	241	116	223	385	142	321
4	12	13	28	60	39	96	102	50	168
5	4	9	13	24	17	49	46	20	70
6	3	3	8	19	4	27	22	8	46
7+	3	7	9	16	11	46	37	13	81
Total	90	101	170	360	187	441	592	233	686
Percent of Total	24.9%	28.0%	47.1%	36.4%	18.9%	44.6%	39.2%	15.4%	45.4%

The remainder of the analysis focused on rail segments with three active crossings that are within 300 ft of each other, as this presents the most likely probability for motorists to hear the locomotive horn and understand it as a warning signal at two crossings downstream of the primary crossing. Since the focus of the analysis was on rail segments with three active crossings, groups of four or more active and mixed crossings were reassessed and categorized into rail segments of three active crossings (e.g., a group of six active crossings were separated into two groups of three active crossings). This identified 111 rail segments with three active crossings within 300 ft of each other.

Figure 2 shows a breakdown of the number of rail segments with three active crossings that are within 300 ft of each other by warning devices present at the crossings. The "All other active" category includes crossings equipped with highway traffic signals, wigwags, bells, and other activated or special active warning devices. Nearly 38 percent of the rail segments contain crossings that are equipped with gates. Rail segments that contain crossings that are equipped with flashing lights are the second most common with 30 percent, followed by rail segments with crossings that are equipped with a mix of active warning devices at 28 percent.

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[3] See Federal Railroad Administration Guide for Preparing U.S. DOT Crossing Inventory Forms.

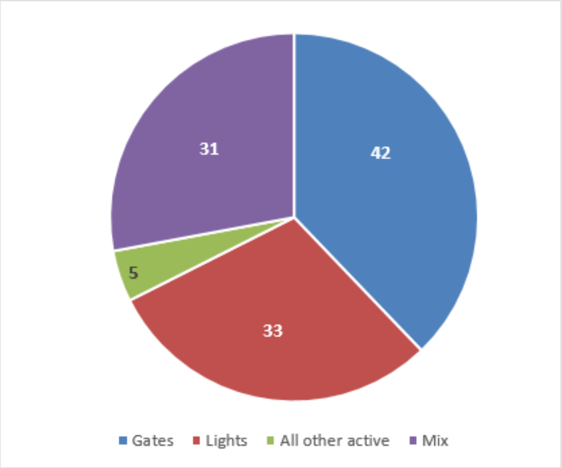

Figure 2. Breakdown of Number of Rail Segments with Three Closely-Spaced Active Crossings (Within 300 ft) by Warning Devices

Freight trains are longer and generally travel slower than passenger rail services, thus they typically block a crossing for a longer period. Roadway users may attempt to beat (i.e., outrun) a train if they know that a crossing will be blocked for an extended period. Figure 3 shows a breakdown of rail segments with three active crossings that are within 300 ft of each other by both warning device and type of rail service. Over 70 percent of the rail segments contain crossings (labeled "All" in Figure 3) that have only freight rail services. Less than three percent of the rail segments contain crossings that have only passenger rail service.

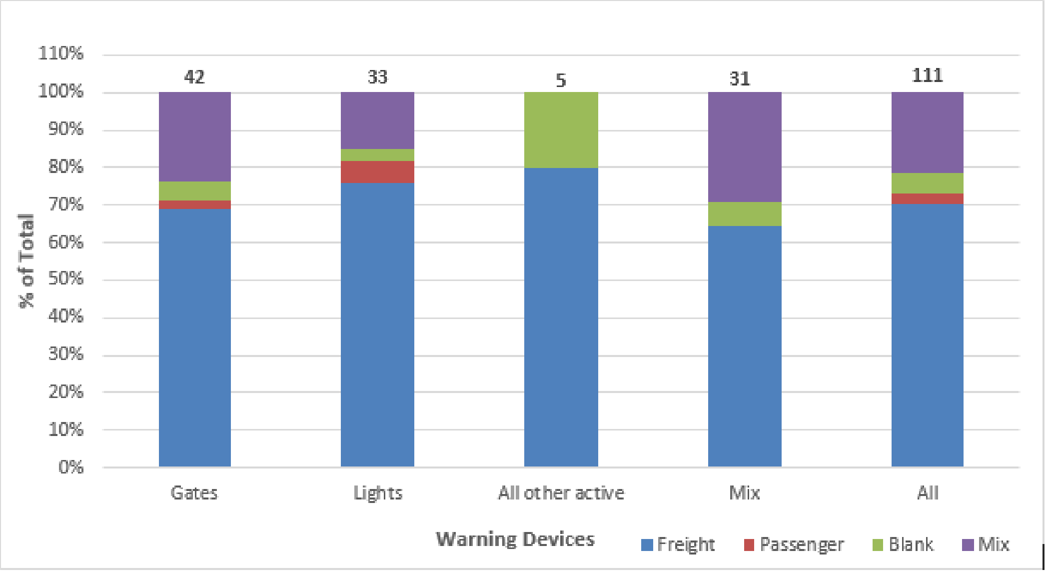

Figure 3. Breakdown of Rail Segments with Three Closely-Spaced Active Crossings (Within 300 ft) by Warning Device and Type of Train

The grade crossing geometries and characteristics chosen for the analysis in this report involved rail segments with three crossings equipped with gates that are within 300 ft of each other. In this setup, a locomotive horn is sounded on approach to the first crossing but not at the second and third crossings. Roadway users at the first crossing would receive the required 20 seconds warning before the arrival of a train but would receive a variable warning time at the second and third crossing depending on the train speed.

Table 4 provides a breakdown of rail segments with three active crossings within 300 ft of each other by maximum timetable speed through the crossing. Nearly 70 percent of the rail segments have a maximum timetable speed of less than or equal to 40 mph through the crossings. If analyzed by individual crossings, 87 percent of the total 333 crossings (i.e., 111 rail segments times three crossings per segment) have a maximum timetable speed of less than or equal to 40 mph.

Table 4. Breakdown of Number of Rail Segments with Three Closely-Spaced Active Crossings (within 300 ft) by Maximum Timetable Speed

Active Crossing Device Type	0-10 mph	11-20 mph	21-30 mph	31-40 mph	41-80 mph	Mix of Maximum Timetable Speed	Total # of Rail Segments
Gates	9	3	4	14	7	5	42
Lights	16	4	3	1	2	7	33
All other active	4	0	1	0	0	0	5
Mix	9	3	6	0	0	13	31
All Active	38	10	14	15	9	25	111

One factor that may affect how the locomotive horn propagates to motorists at closely-spaced crossings and influence roadway users' sightlines is the type of land use and development around a crossing. The functional classification of roadway at crossing ("HWYCLASS") in the GCIS database indicates whether a crossing is located in an urban or rural area and type of land use ("DevelTypID") describes the type of land development near the crossing. Figure 4 shows a breakdown of the number of rail segments with three active crossings that are within 300 ft of each other by functional classification of roadway. Over 80 percent of the rail segments are in an urban designated area.

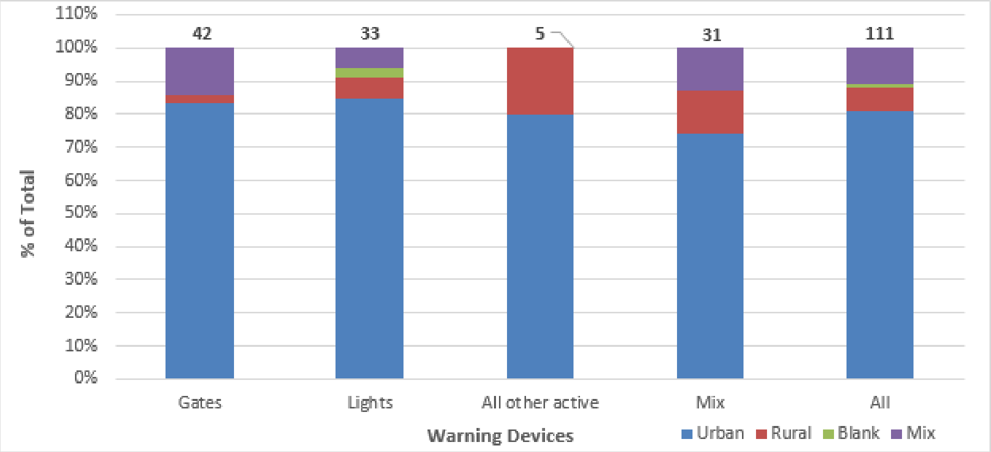

Figure 4. Breakdown of Rail Segments with Three Closely-Spaced Active Crossings (Within 300 ft) by Functional Classification of Roadway

Table 5 shows the breakdown of the number of rail segments with three active crossings that are within 300 ft of each other by type of land use. Nearly 60 percent of the rail segments are in vicinity of residential or commercial area. When analyzed per individual crossing, 86 percent of the 333 crossings are in commercial (51 percent) and residential (35 percent) areas.

Table 5. Breakdown of Rail Segments with Three Closely-Spaced Active Crossings (Within 300 ft) by Land Use

	Open Space	Residential	Commercial	Industrial	Other	Mix	Total # of Rail Segments
Gates	2	9	14	3	0	14	42
Lights	0	10	11	0	0	12	33
All other active	0	2	0	1	0	2	5
Mix	0	5	10	0	0	16	31
All	2	26	35	4	0	44	111

Figure 5 shows the breakdown of the number of rail segments with three active crossings that are within 300 ft of each other by total trains per day through the crossing. Nearly half of the rail segments contain crossings that have between 1 and 10 total trains per day, followed by the "Mix" number of total trains per day. A rail segment is labeled "Mix" if the total trains per day through the three closely-spaced crossings are different. Almost 10 percent of the rail segments are made up entirely of crossings that have less than one total train per day (this is shown in the legend as 0*).

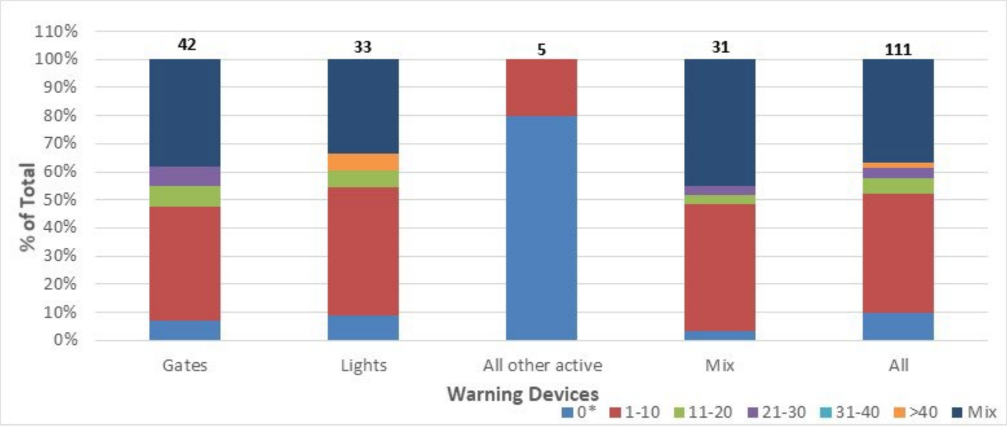

Figure 5. Breakdown of Rail Segments with Three Closely-Spaced Active Crossings (Within 300 ft) by Total Trains Per Day

Table 6 shows a breakdown of the number of rail segments with three active crossings that are within 300 ft of each other by roadway speed limit at the crossing. Nearly 40 percent of rail segments are made up of crossings with roadway speed limits of between 21 and 30 mph, followed by "Mix" of roadway speed limit. A rail segment is labeled "Mix" if the roadway speed limit at the three crossings within the segment is different. Over 60 percent of the crossings in the mix category have roadway speed limits of between 21 and 30 mph.

Table 6. Breakdown of Number Rail Segments with Three Closely-Spaced Active Crossings (Within 300 ft) by Roadway Speed Limit

	0-10 mph	11-20 mph	21-30 mph	31-40 mph	Blank	Mix	Total number of Rail Segments
Gates	0	1	10	0	16	15	42
Lights	0	1	17	3	3	9	33
All other active	0	0	0	3	0	2	5
Mix	0	0	16	0	6	9	31
All	0	2	43	6	25	35	111

The research team used the characteristics detailed in this section to define specific scenarios of interest for the acoustics modeling and analysis presented in Section 5.

4. Acoustic Modeling Framework

Environmental noise modeling and signal detection analyses are typically approached in a source-path-receiver framework. The source of the acoustic signal, the railroad horn, creates a sound, which propagates along a path to the motorist, or receiver. Section 4.1 discusses the source data used to represent the railroad horn signal. Section 4.2 discusses the physical mechanisms accounted for during propagation to the motorist. Section 4.3 discusses the motorist's ambient noise environment, while Section 4.4 discusses the requirements for auditory detection and warning signal recognition. Section 5 discusses how these data were used within the modeling framework to analyze scenarios of interest for closely-spaced crossings. Appendix A contains a glossary of acoustical terminology.

To facilitate acoustic modeling, the research team used the Advanced Acoustic Model (AAM), a suite of software tools that allows users to model vehicle sound levels and auditory detection metrics from any traditional or evolving transportation noise source [9].

4.1 Source Characteristics: Horn Output Level, Frequency, and Directivity

The research team measured locomotive horn source characteristics in April 2001 [10] and provided the necessary data to develop inputs for the AAM. Sound level output and directivity data were measured for four models of locomotive horn (i.e., K-5-LA, K-5-LAR24, RS-3L, and RS-3L-RF) that were installed in two locations (i.e., cab-roof and center) on a GP-40 locomotive. These data are assumed to be reflective of current horn technology, as railway equipment typically has a long lifecycle and no newer horn technologies (such as directive or electronic horns) are in widespread use. As an example, Figure 6 shows the K-5-LA sound level at 200 ft from the cab-roof mounted horn as a function of directivity angle (i.e., theta) around the locomotive, where "theta = 0 degrees" corresponds to the front of the locomotive and direction in which the bell of the horn is pointed. Measurement data were collected on the left side only of the locomotive and assumed symmetrical on the right side.

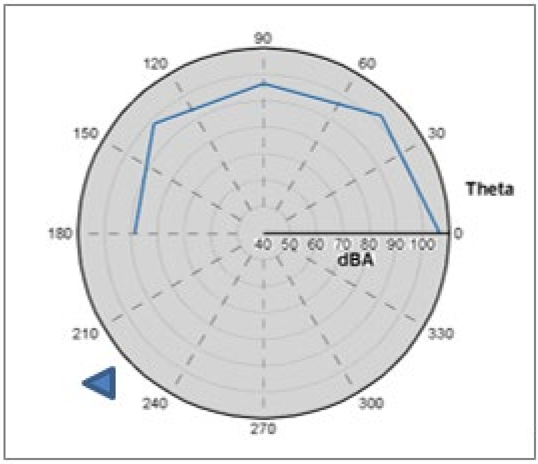

Figure 6. Measured Sound Levels for K-5-LA Horn at 200 ft Distance by Radial Angle

The measured one-third octave-band sound level and directivity data for K-5-LA and RS-3L mounted on the locomotive cab roof were used to develop the three-dimensional sound-source spheres used as inputs to AAM. These horns represent two of the most common horns with all bells forward facing. The cab-roof mounting location provides optimal warning potential.

Additional variants of horn and mounting location may be explored in later phases of this study as warranted.

The sound spheres were created assuming that the horn sound level and directivity characteristics are symmetrical left/right, and do not vary significantly as a function of height above ground level. This assumption is reasonable for the distances of interest in this study (i.e., greater than 200 ft from the horn) but may not be valid for close-in distances (i.e., less than 200 ft) due to locomotive-body shielding effects.

4.2 Sound Propagation

During analysis, AAM adjusts the sound levels from the source sphere for the desired theta angles for propagation losses based on the distance between the source (i.e., horn) and the receiver (i.e., motorist) [11]. Propagation losses include geometric spreading (i.e., 6 dB per distance doubling), atmospheric absorption based on the U.S. standard atmosphere (i.e., 59 degrees F and 70 percent relative humidity), and ground effects due to the interaction of direct and reflected waves. For this analysis, ground effects computations assumed that the ground at the motorist and locomotive locations were at the same elevation with flat, level ground having surface characteristics similar to that of roadside dirt.[4] Shielding due to buildings, barriers, and intervening terrain such as hills was not considered as a factor at this initial stage of the study.

4.3 Vehicle Interior Noise and Transmission Loss

The perceived sound level of the warning signal inside a vehicle is influenced by both the background noise existing in the vehicle interior, which may mask the warning signal, and the transmission loss (i.e., sound isolation characteristics) of the vehicle shell. These factors will vary between vehicles, operating speeds, noise exterior to the vehicle such as other traffic, and interior sound-generating mechanisms controlled by the driver (e.g., ventilation fans and entertainment systems).[5] Thus, the number of background noise conditions is large. For this study, an attempt was not made to represent all conditions, but rather to represent a few conditions likely to occur at grade crossings in the scenarios of interest. Additionally, it was desirable only to source data from existing research and publications; no new data were collected as part of this desktop analysis.[6] Vehicle interior noise data were sourced from two studies representing two conditions: Condition A, 0 mph with max fans/air conditioning and no entertainment systems; and Condition B, 30 mph with no ventilation fans or entertainment systems.

Data for Condition A were sourced from Brach measurements for vehicles manufactured between 1998 and 2007 [13]. The interior noise data were measured while the vehicle was at idle, windows closed, with fans and air conditioning at the maximum setting. Data for Condition B were sourced from Rapoza measurements of seven 1990–1992 model-year automobiles [12].

A comparison of Interior Noise Conditions A and B can be seen in Figure 7. This figure shows the effect of air conditioning fans on high-frequency interior noise. The effect of aerodynamic and road noise from the moving car, typically peaking at frequencies near 500 Hz, is not seen in

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[4] See AAM Technical Manual Sections 2.2.2 and 2.2.3.

[5] Any additional transmission loss or signal masking due to use of headphones or headsets was not considered.

[6] A third study was found which included this type of data, however the operating speed of the vehicle was not reported.

this comparison, likely because these effects are usually most apparent at highway speeds (i.e., >40 mph).

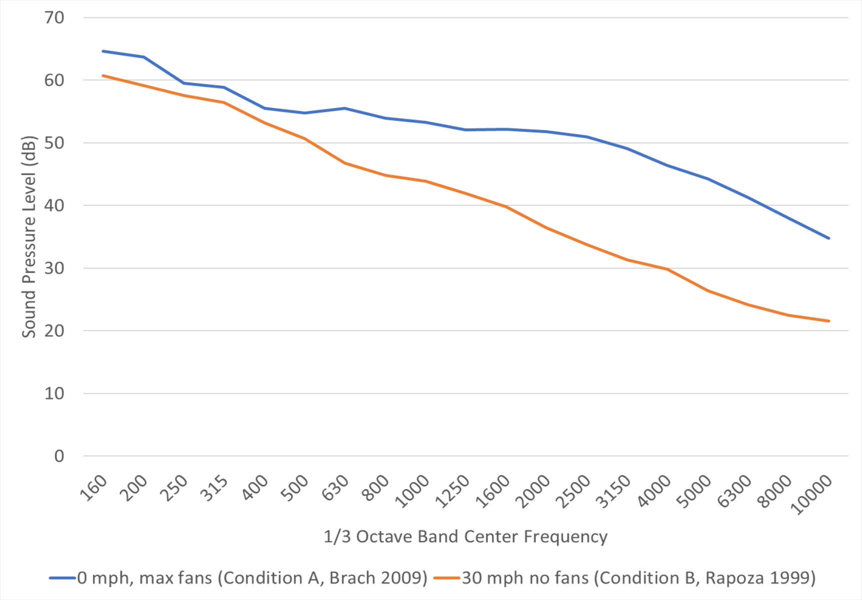

Figure 7. Interior Noise Comparison (Condition A vs Condition B)

Similar measurements of vehicle interior noise were published in 2011 as part of a study on the effectiveness of warning sirens for emergency vehicles [14]. Although this publication did not report a vehicle operating speed, similar sound level trends were observed in the data for the radio off condition (see Figure 8). Also of note is the approximate 10–20 dB increase in sound level for frequencies greater than 300 Hz for the radio-on condition. This is similar to earlier findings summarized in Rapoza 1999.

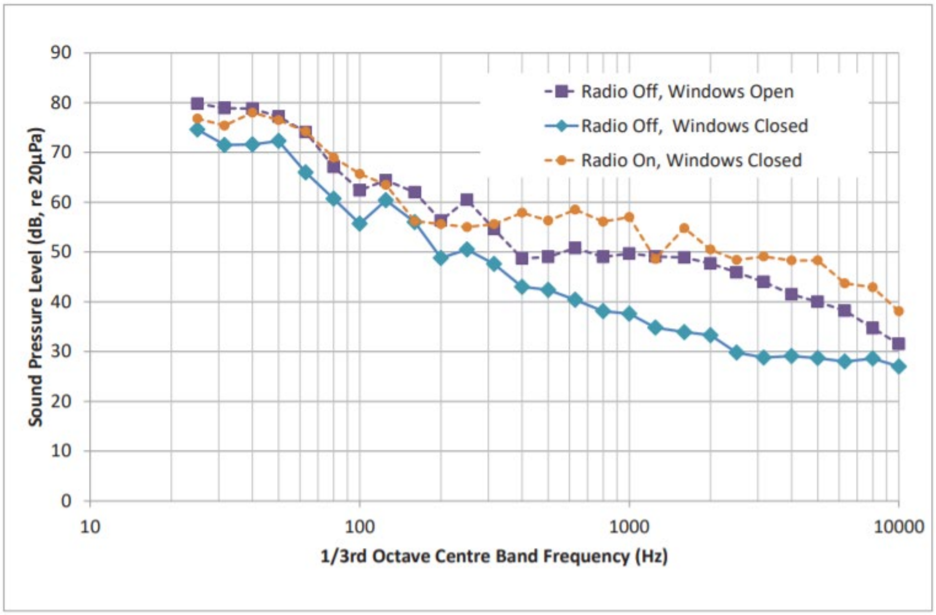

Figure 8. Masked Thresholds While Driving for Three Test Cases, Using L_{eq} Levels over 30 Seconds (reproduced from Howard 2011)

Transmission loss data were sourced from Volpe measurements of seven 1990–1992 model-year automobiles [12]. These measurements were taken with all windows closed using pink noise (i.e., equal energy in each one-third octave band) as the noise source. The measurement data were then averaged across all automobiles measured to derive a final, representative set of transmission loss data.

Vehicle transmission loss was also measured in Brach 2009, however a vehicle (i.e., car) horn was used as a source. Although sufficient to provide a basis for comparison of overall, A-weighted transmission levels, it does not provide data with the granularity for this study and comparable to previous Volpe studies, where data was measured from a source with equal energy across the frequency range of interest (i.e., 100 Hz–4000 Hz).

4.4 Auditory Detection Requirements

To predict if a motorist will hear the locomotive horn, as in previous studies of this nature, a series of works by Fidell, Horonjeff, and Reddingius on aircraft detection provide the basis for specifying the general theory of signal detection in terms of auditory detection (i.e., the ability to detect a signal in the presence of noise) [15] [16]. This work is also summarized in Rapoza 2002 [2].

Within the auditory signal detection model, a detectability index (*d'*), can be calculated as the vector summation of the band-width-adjusted, signal-to-noise ratio (S/N), over the frequency range of interest (i.e., 160 Hz to 10 kHz).

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

Where: η= the efficiency of a human observer at a particular frequency,[7]

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.

This model predicts a detectability index value. Generally, sounds become detectable in a laboratory setting when *d'*>1. Research funded by the National Park Service (NPS) has empirically determined that, in outdoor settings, attentive listeners were able to detect aircraft when *d'* exceeded 5.[8] [9]

The AAM model was used to compute *d'* over an evenly spaced grid of receptor points surrounding a hypothetical railway and grade crossing using the operational scenarios described in Section 5.

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[7] Values for η are provided in Horonjeff, R., and Fidell, S. A, Computer Program for Predicting Audibility of Noise Sources. U.S. AirForce Flight Dynamics Laboratory. AFWAL Technical Report 83-3115, 1983.

[8] Aircraft Noise Model Validation Study, HMMH Report No. 295860.29, January 2003.

[9] The index value, which is in terms of sound pressure, is often converted to a Detectability Level, D'L, where D'L = 10*log10(d'). Thus, the Detectability Level for d'=5 is D'L=7.

5. Acoustic Modeling and Results

The grade crossing characteristics outlined in Section 3 were used to define specific scenarios of interest for acoustics modeling and analysis using the framework outlined in Section 4. Each scenario consists of several parameters, each requiring a definition or input assumption for acoustic modeling. The parameters can be grouped into three categories as outlined in Table 7 and described below.

Table 7. Summary of Scenario Parameters

Grade Crossing Geometry and Characteristics	Driver Behavior	Acoustics (see Section 4)
• Distance between crossings • Train speed / travel time between crossings • Active / passive crossing warning • Roadway speed	• Expectation of a train • Signal recognition • Distraction • Reaction time / stopping distance	• Horn output level, frequency, and directivity characteristics • Sound propagation • Building shielding • Vehicle sound isolation / transmission loss • Headphones • Auditory warning / detection requirements

<u>Grade Crossing Geometry and Characteristics</u>

- Distance between crossings
  - Based on the analysis in Section 3, distance tolerances of 300, 400 or 500 ft were used to group closely-spaced crossings. This distance between crossings determines the distance between the locomotive horn and motorist at each crossing in the group and the distance over which the acoustic signal must propagate at any given moment in time.
- Train speed / travel time between crossings
  - This dictates how far in advance of the crossing the signal will be sounded, and how long the delay time between the end of signal sounding and the train's arrival at crossings downstream of the primary crossing.
- Active / passive crossing warning
  - This is used to derive assumptions for roadway speed and motorist expectations of an approaching train and attentiveness to an audible warning signal.
    - If an active crossing, the motorist is assumed to be stopped before gates (i.e., 25 ft from the centerline of the track) and is attentively listening for the warning signal from an approaching locomotive.[10]
    - If a passive crossing, the motorist is assumed to be on approach to the crossing and may not be attentively listening for warning signals. *Scenarios under this assumption were not included in the initial analysis.*

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[10] Wayside horns were not considered in this study.

- Roadway speed
    - This is used to determine critical warning geometry in passive crossing scenarios where the motorist is not stopped before gates.

Driver Behavior

- Expectation of a train
    - This is used to derive assumptions for signal detection thresholds (see [2]).
        - For motorists at active crossings, the expectation of a train is assumed to be high. The *d'* detectability index must be greater than or equal to 5 for the signal to be considered audible.
        - For motorists at passive crossings, the expectation of a train is assumed to be low. The *d'* detectability index must be greater than or equal to 50 for the signal to be considered audible. This detectability level may also be appropriate for motorists distracted by conversation or other factors (e.g., use of electronic devices).
- Reaction time and stopping distance
    - Reaction time accounts for the time delay between auditory detection and motorist initiation of a stop (i.e., hitting the brakes). Stopping distance is a measure of the time required for a vehicle to stop at a given roadway speed. These parameters are used only in passive crossing scenarios where the motorist is not stopped before gates.

For this initial study, the scenarios of interest were limited to those that were a priori understood by the research team to yield the most likely opportunities for further exploration of locomotive horn sounding needs. The scenarios were limited to active crossings where the distance between crossings was 300 ft. In these scenarios, the horn is most likely to be detected by a motorist and understood as a warning signal at two or more crossings downstream of the primary crossing.

Passive crossing scenarios were not considered; the likelihood of detection is much lower at these crossings, as it is assumed that the motorist may not be attentive. Additionally, the motorist must hear the horn warning signal while on approach to the crossing (and therefore at greater distances) in order to safely stop before entering the crossing envelope.

Limiting scenarios to active crossings only, the parameters that may be varied during analysis include **train speed, type of locomotive horn, and the vehicle interior noise environment**. Train speed was varied between 40 and 50 mph, typical of the types of railways where closely-spaced crossings are located (see Section 3). Based on data described in Section 4, the type of locomotive horn was either K-5-LA or RS-3L, and the vehicle noise environment was assumed to be either at idle with air conditioning fans on max setting (Condition A), or at 30 mph with no air conditioning or fans (Condition B). These scenarios are summarized in Table 8 below.

For each scenario, the project team focused on answers to the following questions that may have additional human factors implications, as discussed in Section 6.

- Is the locomotive horn detectable by the motorist at each crossing in the scenario?
- How long (in seconds) is the locomotive horn detectable?

- How much delay time is there between the time the horn stops sounding and the time the train arrives at the downstream crossings?

Table 8. Summary of Modeling Scenarios

Scenario ID	Distance between crossings (ft) and number of crossings	Locomotive horn	Speed of approaching locomotive (mph)	Interior noise condition
1	300 X 3	K-5-LA	40	A: Idle, max fans
2	300 X 3	R-S-3L	40	A: Idle, max fans
3	300 X 3	K-5-LA	40	B: 30 mph, no fans
4	300 X 3	R-S-3L	40	B: 30 mph, no fans
5	300 X 3	K-5-LA	50	A: Idle, max fans
6	300 X 3	R-S-3L	50	A: Idle, max fans
7	300 X 3	K-5-LA	50	B: 30 mph, no fans
8	300 X 3	R-S-3L	50	B: 30 mph, no fans

5.1 Scenario 1: K-5-LA Horn, 40 mph Train, Interior Noise Condition A

Scenario 1 was defined as a group of three crossings with 300 ft spacing between crossings. The train is assumed to be approaching at 40 mph, using the K-5-LA horn as warning. The motorists are assumed to be stopped at the gates and actively listening for the horn. The interior noise condition of the vehicle is assumed to reflect idle, with air conditioning on using max fans (Condition A). Table 9 provides a summary of the Scenario 1 parameters.

Table 9. Summary of Scenario 1 Parameters

Grade Crossing Geometry and Characteristics	Driver Behavior	Acoustics (see Section 4)
• 300 ft between crossings • Number of crossings - 3 • Train speed / travel time between crossings - 40 mph (44 ft per second) • Active crossing with gates • Driver stopped before gates, 25 ft from track centerline	• High expectation of a train • No distraction • Reaction time / stopping distance - not applicable, driver stopped at gates • Auditory warning / detection requirements: Detectable for attentive listener – d' ≥ 5	• Horn output level (110 dB @ 100 ft) • K-5-LA horn from measurements • Sound propagation - flat, open area • Building shielding - none • Vehicle sound isolation / transmission loss – 1992 measurements • Headphones - none • In-vehicle noise - idle, max fans

These assumptions were used within AAM to model the horn sounding on approach to the three crossings (A, B, and C) in this scenario. Figure 9 shows the ‘detectability footprint’ of the horn sounding. The footprint shows the maximum *d’* from five (i.e., the lower threshold of detectability) to 45 (i.e., yellow to green to blue). This is a plan view of the crossing scenario, where the train is approaching closely-spaced crossings A (at x=0, y=0), B (at x=300, y=0) and C (at x=600, y=0) at 40 mph, running west to east (-1200 to 1200 on the x-axis along a line at y=0). The horn sounding begins 1173 ft in advance of crossing A and lasts for 20 seconds.[11]

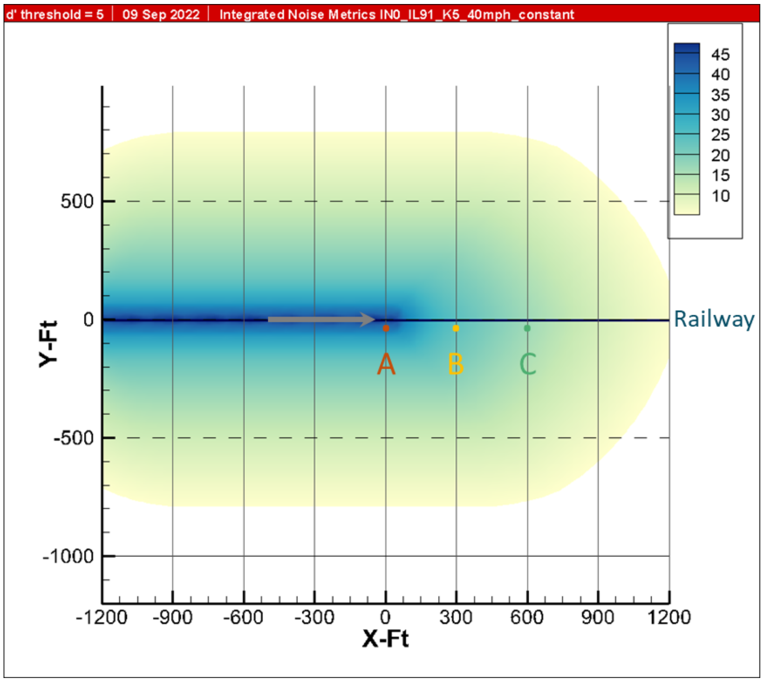

Figure 9. Detectability (d') Footprint for Scenario 1 (K-5-LA Horn, 40 mph Train, Interior Noise Condition A)

The figure indicates that the horn is detectable for an attentive listener for some amount of time (at least 0.5 seconds) during the sounding for up to 1200 ft downstream of the primary crossing (i.e., crossing A). In the lateral (y) direction, the horn sounding remains detectable up to 800 ft from the track centerline (absent any intervening buildings or barriers). This graphic shows that the horn will be detectable for motorists stopped at crossings A, B, and C in this scenario. Note again that the assumption is that gates are down and motorists are stopped at each crossing and not travelling on approach.

Figure 9 provides information on maximum detectability but does not provide information regarding the duration that the horn might be detectable for each driver. Figure 10 shows the detectability time history, indicating how long the horn sounding remains audible for each motorist as well as the delay time between the end of the horn sounding and the arrival of the train at each crossing. For example, a motorist stopped before crossing B, 300 ft downstream of the primary crossing, would likely detect (i.e., hear) the horn for 15 seconds, and then experience a five second delay before the train arrives at the crossing. Note that for motorists B and C, graphics show the warning signal can be heard for ¼ to ½ second beyond the t=0 mark. This reflects the amount of time required for the sound to propagate from the horn to the motorist. In all cases, detectability and delay times noted are rounded to the nearest second.

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[11] At 40 mph, the train travels 1173 ft during the 20 seconds of horn sounding.

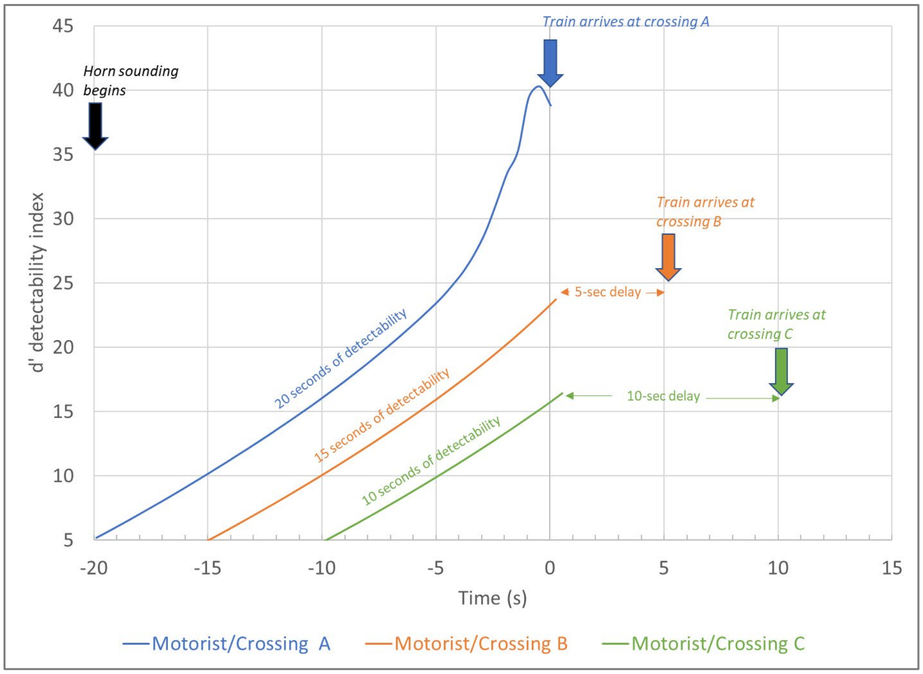

Figure 10. Detectability Time History for Scenario 1 (K-5-LA Horn, 40 mph Train, Interior Noise Condition A)

Note that both figures show that *d'* does not exceed 50, indicating that the warning signal strength would not be sufficient for inattentive motorists approaching passive crossings.

5.2 Scenario 2: RS-3L Horn, 40 mph Train, Interior Noise Condition A

Scenario 2 was defined as a group of three crossings with 300 ft spacing between crossings. Similar to Scenario 1, the train is assumed to be approaching at 40 mph, this time using the RS-3L horn as warning. The motorists are assumed to be stopped at the gates and actively listening for the horn. The interior noise condition of the vehicle is assumed to reflect idle, with air conditioning on using max fans (Condition A). Table 10 provides a summary of the Scenario 2 parameters.

Table 10. Summary of Scenario 2 Parameters

Grade Crossing Geometry and Characteristics	Driver Behavior	Acoustics (see Section 4)
• 300 ft between crossings • Number of crossings - 3 • Train speed / travel time between crossings - 40 mph (44 ft per second) • Active crossing with gates • Driver stopped before gates, 25 ft from track centerline	• High expectation of a train • No distraction • Reaction time / stopping distance - not applicable, driver stopped at gates • Auditory warning / detection requirements: Detectable for attentive listener – d' ≥ 5	• Horn output level (110 dB @ 100 ft) • RS-3L horn from measurements • Sound propagation - flat, open area • Building shielding - none • Vehicle sound isolation / transmission loss – 1992 measurements • Headphones - none • In-vehicle noise - idle, max fans

These assumptions were used within AAM to model the horn sounding on approach to the three crossings (A, B, and C) in this scenario. Figure 11 shows the Scenario 2 ‘detectability footprint’ of the horn sounding, where the maximum *d’* runs from five (i.e., the lower threshold of detectability) to 45 (i.e., yellow to green to blue).

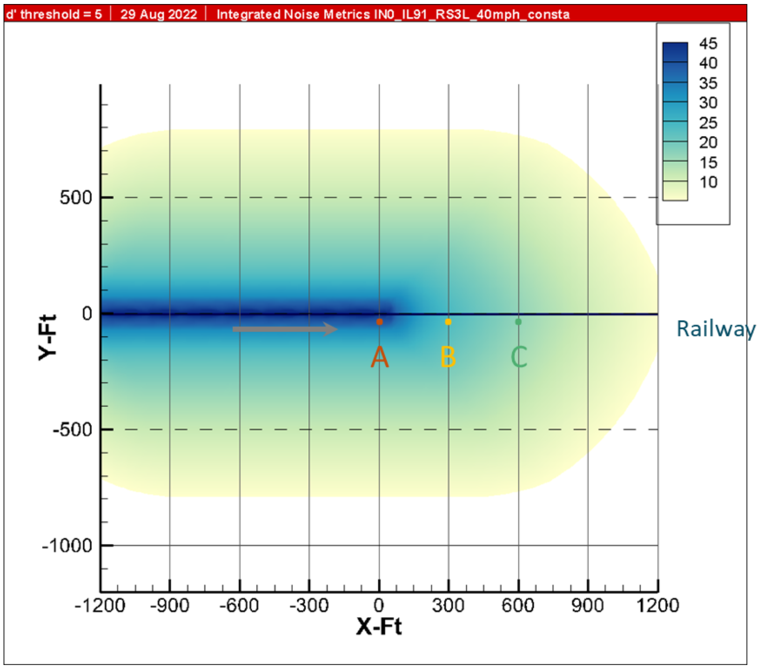

Figure 11. Detectability Footprint for Scenario 2 (RS-3L Horn, 40 mph Train, Interior Noise Condition A)

The results shown for the RS-3L horn are nearly identical to the results from Scenario 1 with the K-5-LA horn; the horn is detectable for an attentive listener for some amount of time (at least 0.5 seconds) during the sounding up to 1200 ft downstream of the primary crossing (crossing A). In the lateral (y) direction, the horn sounding remains detectable up to ~800 ft from the track centerline (absent any intervening buildings or barriers). This graphic shows that the horn will be detectable for motorists stopped at crossings A, B, and C in this scenario. Note again that the assumption is that gates are down and motorists are stopped at each crossing and not travelling on approach.

Figure 12 shows the detectability time history indicating how long the horn sounding remains audible for each motorist as well as the delay time between the end of the horn sounding and the arrival of the train at each crossing. Again, results are nearly identical to those of the K-5-LA horn, although the RS-3L horn is detectable for slightly longer (i.e., one second) at crossing B and crossing C. Figure 13 shows results for both Scenario 1 and Scenario 2 to allow for direct comparison.

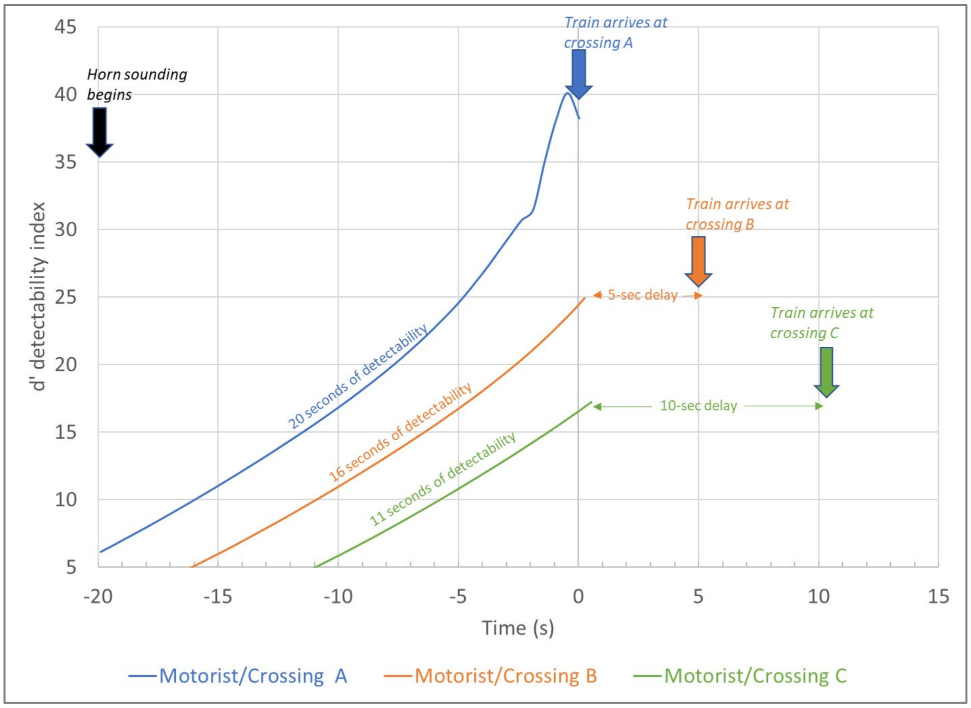

Figure 12. Detectability Time History for Scenario 2 (RS-3L Horn, 40 mph Train, Interior Noise Condition A)

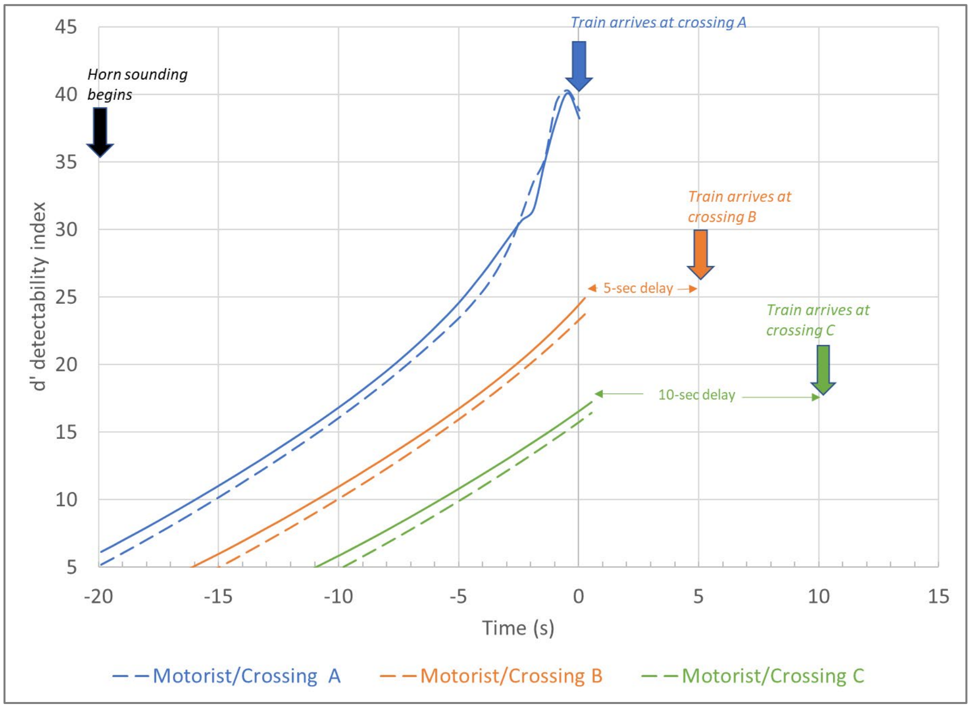

Figure 13. Detectability Time History for Scenario 1 (K-5-LA, dashed lines) and Scenario 2 (RS-3L Horn, solid lines), both with 40 mph Train and Interior Noise Condition A.

Because the two horns show nearly identical results, the team did not consider the horns separately. Instead, the team examined results for only the K-5-LA horn. Therefore, results for Scenarios 4, 6, and 8 are considered equivalent to Scenarios 3, 5, and 7.

5.3 Scenario 3: K-5-LA Horn, 40 mph Train, Interior Noise Condition B

Scenario 3 was defined as a group of three crossings with 300 ft spacing between crossings. The train is assumed to be approaching at 40 mph, using the RS-3L horn as warning. The motorists are assumed to be stopped at the gates and actively listening for the horn. The interior noise condition of the vehicle is assumed to reflect 30 mph, with no ventilation fans (Condition B). Although a bit contradictory to the scenario assumptions (i.e., motorist stopped), Condition B interior noise at 30 mph is included in this analysis to help illustrate the effects of a range of possible interior noise conditions. Most notably, Condition B represents a condition with no ventilation fans running and thus is quieter overall than Condition A. Table 11 provides a summary of the Scenario 3 parameters.

Table 11. Summary of Scenario 3 Parameters

Grade Crossing Geometry and Characteristics	Driver Behavior	Acoustics (see Section 4)
• 300 ft between crossings • Number of crossings - 3 • Train speed / travel time between crossings - 40 mph (44 ft per second) • Active crossing with gates • Driver stopped before gates, 25 ft from track centerline	• High expectation of a train • No distraction • Reaction time / stopping distance - not applicable, driver stopped at gates • Auditory warning / detection requirements: Detectable for attentive listener – d' ≥ 5	• Horn output level (110 dB @ 100 ft) • K-5-LA horn from measurements • Sound propagation - flat, open area • Building shielding - none • Vehicle sound isolation / transmission loss – 1992 measurements • Headphones - none • In-vehicle noise - 30 mph, no fans

These assumptions were used within AAM to model the horn sounding on approach to the three crossings in this scenario. Figure 14 shows the ‘detectability footprint’ of the horn sounding. The footprint shows the maximum *d’* from five (i.e., the lower threshold of detectability) to 45 (i.e., yellow to green to blue).

Figure 14 indicates that the horn is detectable for an attentive listener for some amount of time (at least 0.5 seconds) during the sounding for up to 2500 ft downstream of the primary crossing (i.e., crossing A). In the lateral (y) direction, the horn sounding remains detectable up to ~1700 ft from the track centerline (absent any intervening buildings or barriers). This graphic shows that the horn will be detectable for motorists stopped at crossings A, B, and C in this scenario. Note again that the assumption is that gates are down and motorists are stopped at each crossing and not travelling on approach. Interior noise Condition B is overall quieter than Condition A, as the ventilation fans contribute most to the interior noise. Thus, the horn is detectable over a larger area and for longer durations. Note also that the scale in Figure 14 has been expanded to show the full 2500 ft distance.

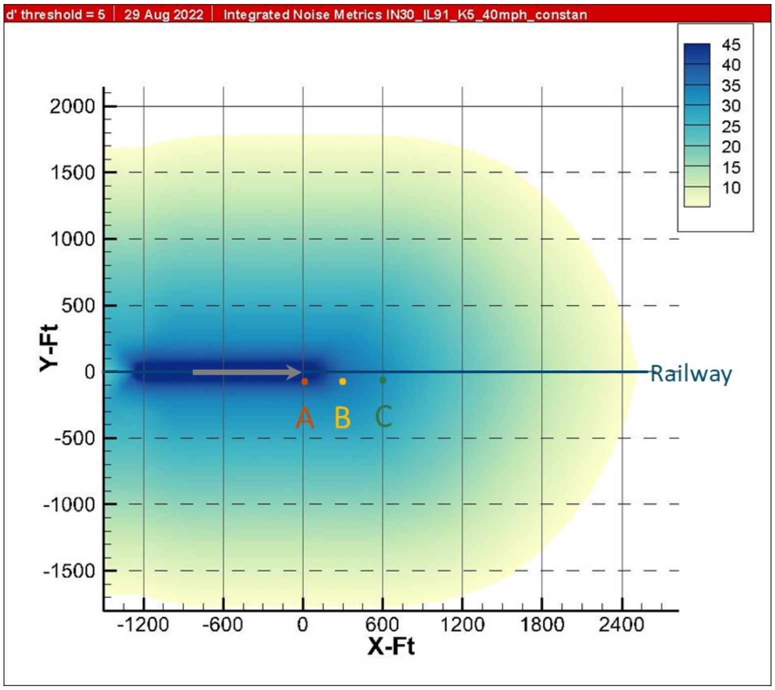

Figure 14. Detectability Footprint for Scenario 3 (K-5-LA Horn, 40 mph Train, Interior Noise Condition B)

Figure 15 shows the detectability time history indicating how long the horn sounding remains audible for each motorist as well as the delay time between the end of the horn sounding and the arrival of the train at each crossing. This time the horn remains detectable for 20 seconds for all motorists, although there will still be delays of 5 and 10 seconds at crossings B and C, respectively.

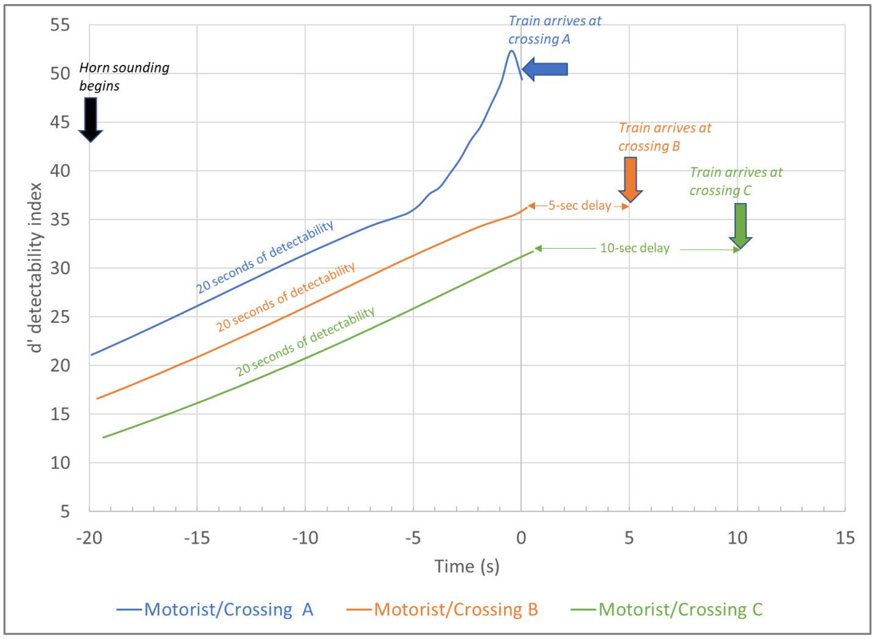

Figure 15. Detectability Time History for Scenario 3 (K-5-LA Horn, 40 mph Train, Interior Noise Condition B)

Overall, Condition B is quieter and allows for detectability at longer distances and for a longer duration than Condition A. Figure 16 shows results for both Scenarios 1 and 3 to allow for direct comparison of the results of Condition A (dashed lines) and Condition B (solid lines).

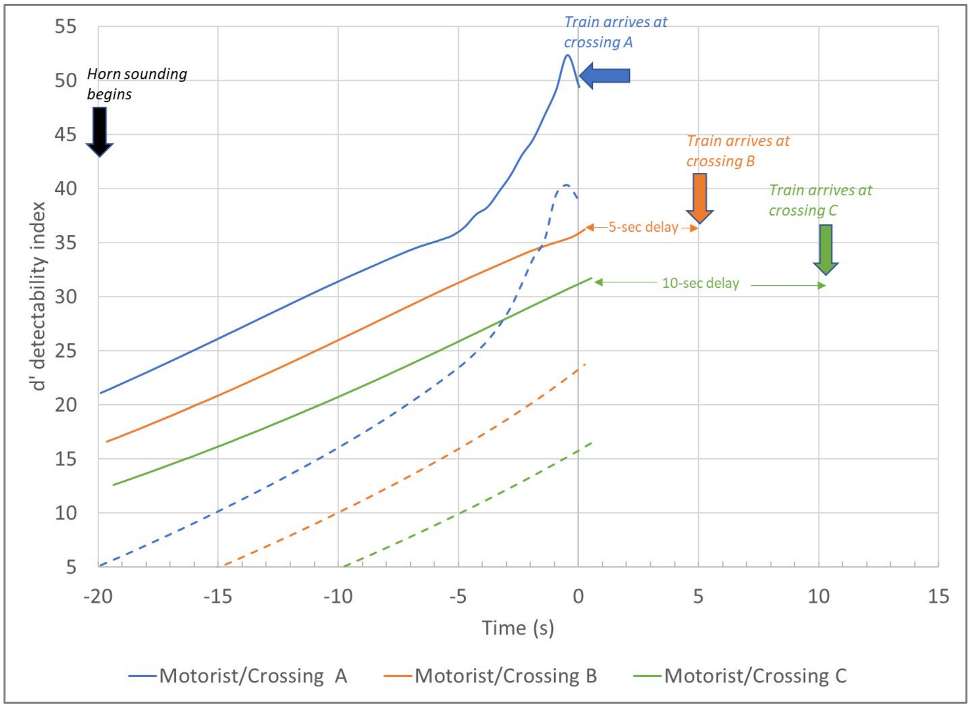

Figure 16. Detectability Time History for Scenario 1 (Interior Noise Condition A, dashed lines) and Scenario 3 (Interior Noise Condition B, solid lines), Both with K-5-LA Horn and 40 mph Train

Therefore, the remaining analysis scenarios will only consider Condition A, as this represents a condition that is more conservative and more likely to occur in practice (i.e., most motorists use ventilation fans while operating a vehicle).

5.4 Scenario 4: RS-3L Horn, 40 mph Train, Interior Noise Condition B

Scenario 4 is assumed to have results similar to Scenario 3.

5.5 Scenario 5: K-5-LA Horn, 50 mph Train, Interior Noise Condition A

Scenario 5 was defined as a group of three crossings with 300 ft spacing between crossings. The train is assumed to be approaching at 50 mph, using the K-5-LA horn as warning. The motorist is assumed to be stopped at the gates and actively listening for the horn. The interior noise condition of the vehicle is assumed to reflect 0 mph, with max ventilation fans (Condition A). Table 12 provides a summary of the Scenario 5 parameters.

Table 12. Summary of Scenario 5 Parameters

Grade Crossing Geometry and Characteristics	Driver Behavior	Acoustics (see Section 4)
• 300 ft between crossings • Number of crossings - 3 • Train speed / travel time between crossings - 50 mph (44 ft per second) • Active crossing with gates • Driver stopped before gates, 25 ft from track centerline	• High expectation of a train • No distraction • Reaction time / stopping distance - not applicable, driver stopped at gates • Auditory warning / detection requirements: Detectable for attentive listener – d' ≥ 5	• Horn output level (110 dB @ 100 ft) • K-5-LA horn from measurements • Sound propagation - flat, open area • Building shielding - none • Vehicle sound isolation / transmission loss – 1992 measurements • Headphones - none • In-vehicle noise - 0 mph, max fans

These assumptions were used within AAM to model the horn sounding on approach to the three crossings in this scenario. Figure 17 shows the 'detectability footprint' of the horn sounding.

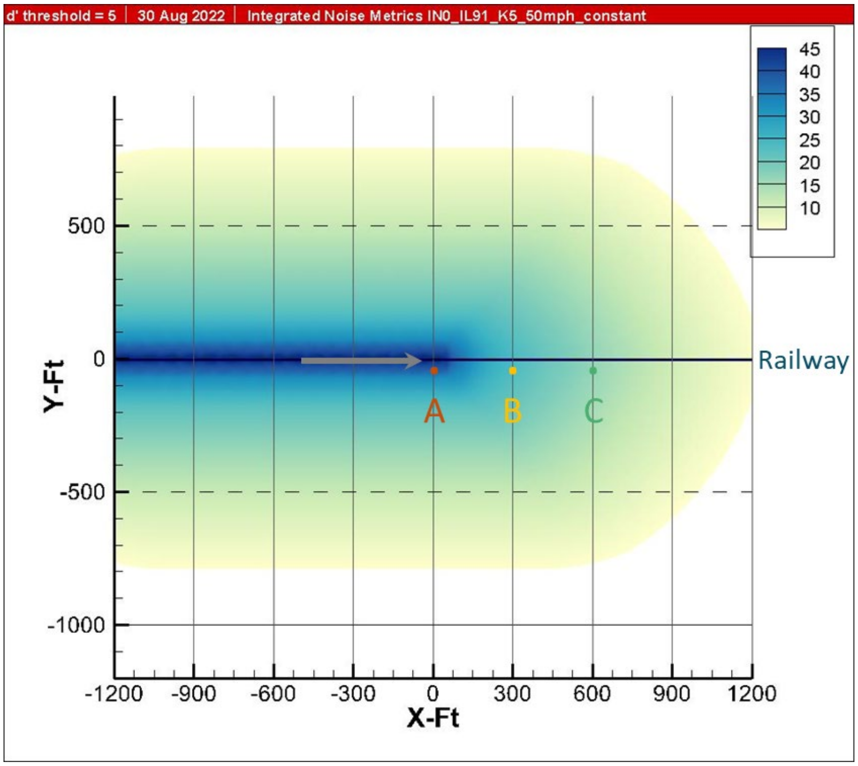

Figure 17. Detectability Footprint for Scenario 5 (K-5-LA Horn, 50 mph Train, Interior Noise Condition A)

The footprint shows the maximum *d'* from five (i.e., the lower threshold of detectability) to 45 (i.e., yellow to green to blue). This is a plan view of the crossing scenario, where the train is approaching closely spaced crossings A (at x=0, y=0), B (at x=300, y=0), and C (at x=600, y=0) at 50 mph, running west to east along a line at y=0. The horn sounding begins 1,320 ft (1/4 mile) in advance of the crossing and lasts for 19 seconds, stopping when the train reaches crossing A. The maximum sounding distance required by FRA regulations is 1,320 ft.

Figure 17 indicates that the horn is detectable for an attentive listener for some amount of time (at least 0.5 seconds) during the sounding for up to 1,200 ft downstream of the primary crossing (crossing A). In the lateral (y) direction, the horn sounding remains detectable up to ~800 ft from the track centerline. This graphic shows that the horn will be detectable for motorists stopped at crossings A, B, and C in this scenario. Note again that the assumption is that gates are down and motorists are stopped at each crossing and not travelling on approach. Note that the detectability footprint results are similar between Scenarios 1 and 5 for the K-5-LA horn, as the maximum detectability *level* does not change based on train speed. Changes due to train speed are reflected in the detectability time history results summarized next.

Figure 18 shows the detectability time history indicating how long the horn sounding remains audible for each motorist as well as the delay time between the end of the horn sounding and the arrival of the train at each crossing. This time, the train is traveling faster, and the horn remains detectable for 16 seconds at crossing A, 12 seconds of detectability followed by a 4 second delay before the train arrives at crossing B, and 8 seconds of detectability followed by an 8 second delay before the train arrives at crossing C. Figure 19 shows the results for both Scenario 1 and Scenario 5 on the same graphic, illustrating the difference in detectability time and delay time between the 40 mph train and 50 mph train.

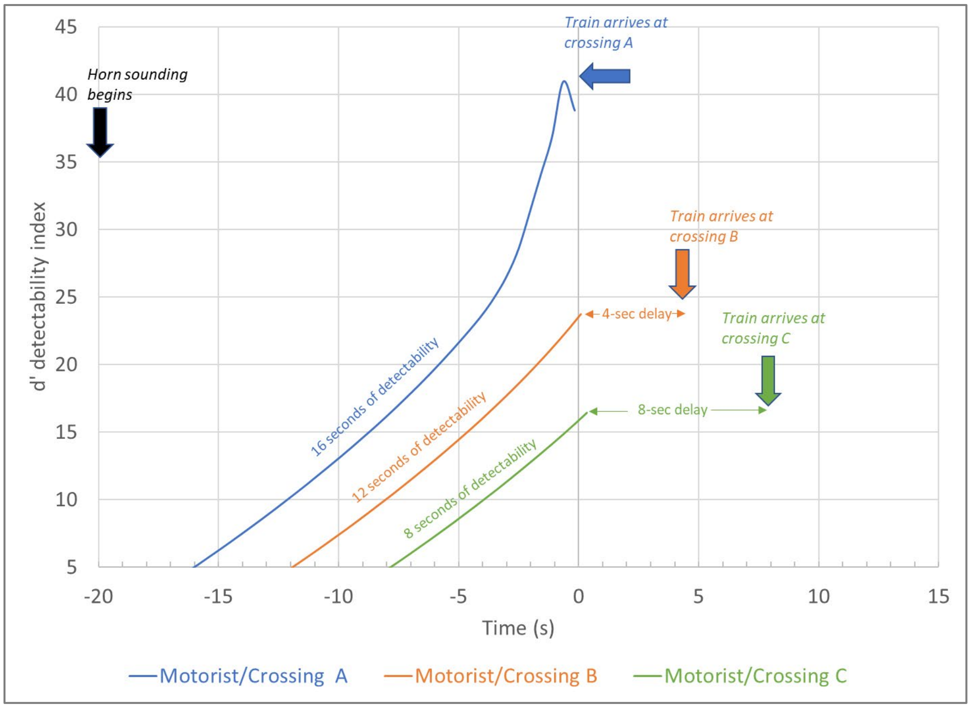

Figure 18. Detectability Time History for Scenario 5 (K-5-LA Horn, 50 mph Train, Interior Noise Condition A)

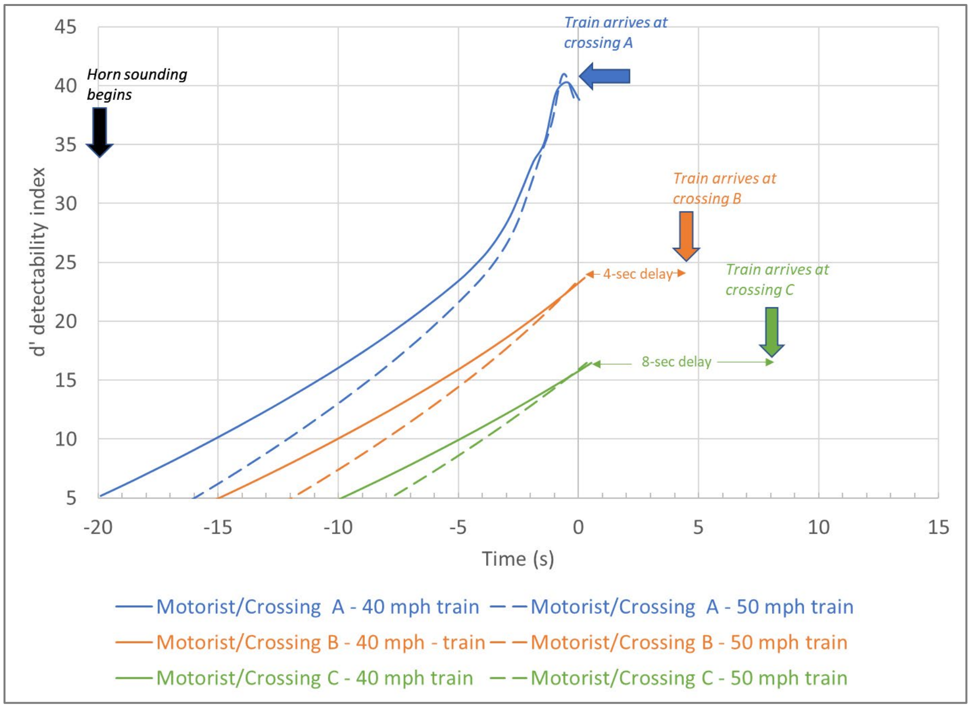

Figure 19. Detectability Time History for Scenario 1 (40 mph Train, solid lines) and Scenario 5 (50 mph Train, dashed lines)

5.6 Scenario 6: RS-3L Horn, 50 mph Train, Interior Noise Condition A

Scenario 6 is assumed to have results similar to Scenario 5 due to similarities between horns.

5.7 Scenario 7: K-5-LA Horn, 50 mph Train, Interior Noise Condition B

Based on the results of Scenario 3 with K-5-LA horn and interior noise Condition B, and Scenario 5 with K-5-LA horn and 50 mph train, we can assume the following for Scenario 7:

- The quieter Condition B with K-5-LA horn will allow for detectability at distances out to 2,500 ft, and will be detectable for the entire horn sounding for motorists at crossings A, B, and C. The increase in train speed (40 mph in Scenario 3 vs 50 mph in Scenario 7) will not have an effect on horn detectability for the motorists.
- The delay time for motorists at crossings B and C will be 4 and 8 seconds, respectively.

5.8 Scenario 8: RS-3L Horn, 50 mph Train, Interior Noise Condition B

Scenario 8 is assumed to have results similar to Scenario 7 due to similarities between horns.

5.9 Discussion/Summary

The results of the acoustic modeling analysis are summarized and compared in Table 13 and Table 14. This analysis showed similar results for different locomotive horns and different train speeds at the three crossing locations separated by 300 ft. The locomotive horns met the detectability criteria out to a minimum of 1,200 ft in all scenarios. The main differences observed were related to interior noise conditions and delay between the stop of the horn and the arrival of a train at a crossing (i.e., train speed). Specifically, a significant increase in detectability was observed for Condition B, which is overall quieter than Condition A, as the ventilation fans contribute significantly to the interior noise. In addition, the delay between the stop of the horn and the arrival of a train at a crossing decreased as train speed increased, without a significant change in detectability.

Table 13. Summary of Detectability Footprint Length for Each Scenario – Distance Downstream of Primary Crossing at Which Horn May Be Detectable for Motorists (Absent Intervening Buildings, Barriers, etc.)

Scenario ID	Locomotive horn	Speed of approaching locomotive (mph)	Interior noise condition	Distance at which horn remains detectable (ft)
1	K-5-LA	40	A	1200
2	R-S-3L	40	A	1200
3	K-5-LA	40	B	2500
5	K-5-LA	50	A	1200

Table 14. Summary of Detectability and Delay Time for Motorists at Crossings A, B and C for Scenarios 1 and 5 (K-5-LA Horn, Interior Noise Condition A)

		Crossing A		Crossing B		Crossing C	
Scenario	**Train Speed (mph)**	**Detectability (s)**	**Delay (s)**	**Detectability (s)**	**Delay (s)**	**Detectability (s)**	**Delay (s)**
1	40	20	0	15	5	10	10
5	50	16	0	12	4	8	8

For each scenario, the project team focused on answers to the following questions that may have additional human factors implications, as discussed in Section 6.

- Is the locomotive horn detectable by the motorist at each crossing in the scenario?
    - Yes (detectable out to a minimum of 1200 ft in all scenarios)
- How long (in seconds) is the locomotive horn detectable?
    - 8–15 seconds for motorists downstream of the primary crossing
- How much delay time is there between the time the horn stops sounding and the time the train arrives at the downstream crossings?
    - 4–10 seconds for motorists downstream of the primary crossing

6. Human Factors Implications

As described above, there are scenarios within which drivers can hear (i.e., detect) the locomotive horn as they approach each of the crossings within a quasi-quiet zone. While hearing the locomotive horn can help a driver anticipate a train, simply hearing the locomotive horn may not be sufficient to elicit the behavior that is desired of the driver. A quasi-quiet zone, and especially those with certain characteristics, may have the potential to introduce additional risk if not carefully considered.

There are a number of factors that may influence a driver's willingness to stop for a train at a highway-rail grade crossing. Some visual signals are very clear, such as gates that limit access to the tracks and bells and lights that flash as the train approaches. These active protections are generally quite effective at preventing vehicles and pedestrians from entering the right-of-way as a train approaches, while providing access to cross the tracks at that location when trains are not approaching. These protective measures can be undermined by certain factors, however, such as a perceived lack of reliability or by extensive wait times. Here, "wait time" refers to the length of time that a driver must wait between the activation of the crossing bells/lights/gates and when the train arrives at the crossing.

Research has shown that longer wait times at active crossings can increase risky behavior [17] [18] [21]. The specifics of what constitutes "longer" seems to vary by study and is likely situation dependent. Similarly, increased variability in the wait time is another factor that may contribute to increased risk taking [20] [21]. A driver who traverses a crossing often and is accustomed to a certain wait time may change their willingness to violate at that crossing if the wait time deviates from their expected wait time.

Considering the specific scenarios in this research, there is the potential for an increase in the variability of warning time.[12] The "warning time" in this case is represented by the difference in time between when the driver hears the locomotive horn and when the train actually arrives. If the warning time is consistent and of a reasonable length (e.g., 20 seconds), then drivers and pedestrians can predict their approximate wait time. However, if the warning time is too long or too variable, then drivers may lose faith in the system. At a crossing like those described in this report, the warning times will likely vary for the crossings on either end of the quasi-quiet zone. Warning times will be shorter for trains approaching from one direction and longer for trains approaching from the other direction.

Consider, for example, the scenario depicted in Figure 20. Three active crossings with gated protections (A, B, and C) are equally spaced, 300 ft apart from one another. Two railroad tracks go through these crossings with trains that may approach from the West (Train 1 in this example) or the East (Train 2 in this example). If Train 1 were to sound its horn only upon approach to provide drivers and pedestrians at Crossing A with the required 20 second warning (but not again for the next crossings), the warning time would be longer for Crossing B and Crossing C. Exactly how much longer the warning time will be depends on how fast the train is moving through the crossing; a slower moving train will generate larger warning time discrepancies than a faster moving train. Drivers and pedestrians at Crossing A would always experience a shorter

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[12] Three crossings each had the following criteria: each within 300ft of one another and each have active gated protections.

warning time for trains coming from the west than drivers and pedestrians at Crossing B or Crossing C.

Conversely, the opposite is true for trains approaching from the east. As Train 2 approaches, the warning time will always be shorter for drivers and pedestrians at Crossing C, as compared to Crossing B and Crossing A. With three closely spaced crossings, it is unlikely that the wait time for the last crossing will differ by a large amount of time, unless the train happens to be moving very slowly or comes to a stop while traversing the crossings. What may be an issue, however, is that Crossing A and Crossing C will experience an increase in the variability of warning time as a function of the direction of the approaching train. A vehicle driver who becomes accustomed to a warning time associated with one direction of train travel, perhaps simply by chance, may be unprepared for a different warning time. That variability could increase risky behavior.

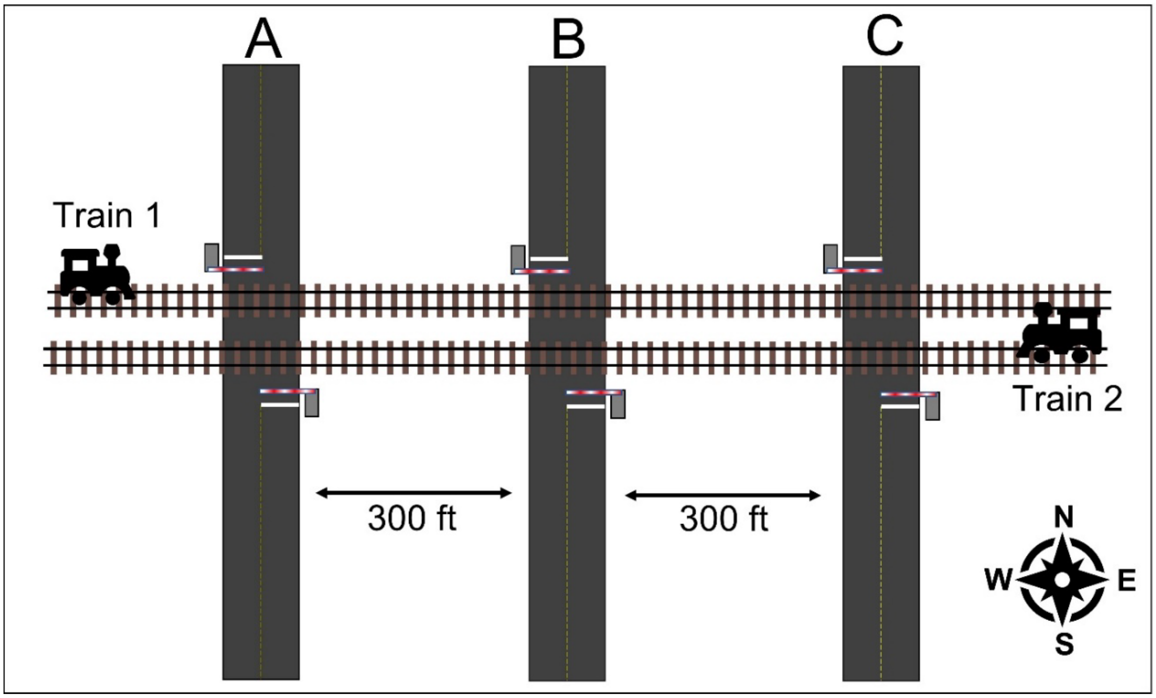

Figure 20. Example Scenario of Closely-Spaced Crossings

While the introduction of a quasi-quiet zone will necessarily increase the variability in the warning time at a given crossing, the specific impact may depend on a number of other factors. As an example, the variability in the warning time is likely to be a bigger influence for a driver who experiences these crossings with frequency so that they have an expectation of a “typical” warning time. Variability is likely less of a factor for a driver who experiences railroad crossings rarely.

There are other factors that may modify the risk of violating an active crossing in this scenario but may not be predictable enough to inform action. For example, the presence of other vehicles may reduce the likelihood that the lead car will violate an active crossing [18]. However, given traffic variability through any given day, it is not possible to predict if other vehicles will provide a safety benefit at any given moment.

An Australian study indicated that pedestrians are more likely to violate an active crossing before a train arrived [22]. This same study also indicated that pedestrians and other vulnerable road users (VRUs) relied on auditory signals more than motor vehicle drivers, who relied more on visual signals to make decisions about safe actions. If this is true for American pedestrians as well, then this could be valuable information since pedestrians at the second and third crossing of a quasi-quiet zone may be presented with longer than expected wait times and could be more prone to violation. Increasing the warning time for those crossings could be more consequential for pedestrians than for motor vehicle drivers if pedestrians indeed rely primarily on that auditory warning to make decisions about their actions.

One way to combat the potential challenges of increasing the variability of the train warning time would be to increase the potential for the driver or pedestrian to use another cue to identify the approaching train. Crossings with clear sight lines to the left and right provide drivers with an opportunity to see as well as hear the train as it approaches, especially if the track through the crossing is straight. Providing drivers with an opportunity to use visual cues to see the approaching train may be especially helpful. As the warning time extends beyond the expected time, the opportunity to see the approaching train may help drivers confirm that the train is still approaching. Note that the acoustic scenarios and results described in Section 5 assume that there are clear sight lines for sound propagation. More research is needed to confirm if clear sightlines are required for auditory detection and are an effective way to maintain safety if warning time variability increases.

7. Conclusions and Discussion

The objective of this research was to determine the feasibility of altering the locomotive horn sounding pattern of repetition at closely-spaced grade crossings by exploring specific geometries and warning requirements for motorists in advance of such crossings.

Acoustic modeling was conducted on five example scenarios where rail segments composed of three grade crossings equipped with gates are separated by 300 ft and have clear sight lines. The results of the acoustic modeling analysis showed similar results for different locomotive horns and different train speeds. When sounded *only* on approach to the primary crossing, the locomotive horn would be detectable between 8 and 15 seconds for motorists stopped at the gates downstream of the primary crossing across the scenarios. Additionally, there would be a range of 4 to 10 seconds of delay between the last horn blast and the moment the train arrives at the downstream crossing. It was also illustrated that the locomotive horn would meet the auditory detection criteria out to a minimum of 1,200 ft downstream of the primary crossing in all scenarios.

Auditory detection alone, however, may not be sufficient to ensure that drivers at these crossings will make safe choices. Research suggests that variability in warning times (i.e., the amount of time the horn is detectable) may increase the potential for drivers to consider violating the crossing, especially if they have become accustomed to a certain wait time. Warning times at each of the three crossings will differ if the locomotive horn is only sounded prior to arrival at the first crossing. Trains coming from different directions will have different warning times at the same crossing. These increases in the variability of the warning time have the potential to increase risk-taking behaviors by drivers waiting for the train.

It may be possible to address this by providing redundant ways for drivers to detect the presence of the train. For example, if the closely-spaced crossings have good sight lines, drivers may be better able to detect the approaching train. This way, even if the warning time extends beyond their expected wait time, they will be able to see the approaching train before they consider violating the crossing.

For this analysis, a conservative scenario was analyzed: active grade crossings, crossings spaced 300 ft (or less) from each other, known interior noise levels, straight track, current average horn technology and sounding pattern, specific train speeds, clear lines of sight without building or terrain shielding of the warning signal, and automobiles stopped at the crossings with the drivers expecting a pending train at their crossings. While this covers many closely spaced crossing configurations in the U.S., it does not cover all scenarios and configurations.

The results from this analysis confirm that further exploration is needed on this topic, including assessing the feasibility and effectiveness for both detectability and driver response, to only sounding the locomotive horn prior to arriving at the first in a series of closely-spaced grade crossings. A comprehensive risk assessment on the potential impacts of altering the locomotive horn pattern of repetition, along with further study of additional scenarios, should be completed.

8. Limitations

This report and analysis is based on a common, conservative scenario where, given the analysis parameters discussed in Section 5, a single horn sounding may provide effective auditory warning for multiple, active grade crossings. However, the scenario is limited and may not be applicable to all multiple, closely-spaced crossings in the U.S. As discussed in Section 6, a quasi-quiet zone, and especially those with certain characteristics, may have the potential to introduce additional risk if not carefully considered.

The following factors were specifically not covered in this analysis:

- Grade crossing spacing greater than 300 ft
- Trains traveling at speeds less than 40 mph or greater than 50 mph
- Motorists where the vehicle environments may be louder-than-normal (e.g., loud radio, loud engine/exhaust)
- Motorists in moving vehicles over a range of speeds
- Motorists wearing in- or -over-ear headphones or headsets
- Distracted motorists
- Environments where buildings or terrain features block the warning signal propagation line-of-sight
- Passive crossings
- Two-way train traffic
- Multiple crossings on curved track

In all cases, these factors will decrease the likelihood that the warning signal is detected and interpreted correctly and increase the risk of a crossing incident. In addition, even though they may be more effectively alerted by the warning signal than a motorist, the effectiveness of the warning signal for pedestrians at consecutive grade crossings (including those wearing in- or -over-ear headphones or headsets) was not investigated in this analysis.

The impacts of the following factors that could improve the understanding of the warning signal or improve its effectiveness were also not investigated in this analysis:

- Minimum detectability index level and duration needed for effective warning
- Additional or nontraditional locomotive warning signals (including supplementing the warning signal if the delay to the crossing is greater than 20 seconds)
- Additional wayside or grade crossing warning signals

A supplemental investigation into these factors would further improve the understanding of the locomotive horn sounding needs across multiple, consecutive, closely-spaced grade crossings in a wider range of environments.

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Appendix A. Acoustical Terminology

This section presents pertinent terminology used throughout the report. Note: Definitions are generally consistent with those of the American National Standards Institute (ANSI).

A-WEIGHTING - A frequency-based methodology used to account for changes in human hearing sensitivity as a function of frequency. The A-weighting network de-emphasizes the high (6.3 kHz and above) and low (below 1 kHz) frequencies, and emphasizes the frequencies between 1 kHz and 6.3 kHz, in an effort to simulate the relative response of human hearing.

ACOUSTIC ENERGY - Commonly referred to as the mean-square sound-pressure ratio, sound energy, or just plain energy, acoustic energy is the squared sound pressure (often frequency weighted) divided by the squared reference sound pressure of 20 µPa, the threshold of human hearing. It is arithmetically equivalent to $10^{LEV/10}$, where LEV is the sound level, expressed in decibels.

DECIBEL (dB) - A unit of measure for defining a noise level or a noise exposure level. The number of decibels is calculated as ten times the base-10 logarithm of the squared sound pressure (often frequency weighted), divided by the squared reference sound pressure of 20 µPa, the threshold of human hearing.

EQUIVALENT SOUND LEVEL (L_{AeqT}) - Ten times the base-10 logarithm of the time-mean-square, instantaneous A-weighted sound pressure, during a stated time interval, T (where $T=t_2-t_1$, in seconds), divided by the squared reference sound pressure of 20 µPa, the threshold of human hearing.

FREQUENCY - For a function periodic in time, the reciprocal of the period (the smallest increment of an independent variable for which a function repeats itself).

LINE-OF-SIGHT - The direct line between a sound source and a noise analysis location.

SOFT GROUND - Any highly absorptive surface in which the phase of the sound energy is changed upon reflection; examples include terrain covered with dense vegetation or freshly fallen snow. (Note: At grazing angles greater than 20 degrees, which can commonly occur at short ranges, or in the case of elevated sources, soft ground becomes a good reflector and can be considered hard ground).

SOUND - Auditory sensation evoked by the oscillation in pressure, stress, particle displacement, particle velocity, etc., in a medium with internal forces (e.g., elastic or viscous), or the superposition of such propagated oscillations.

SOUND PRESSURE LEVEL (SPL) - Ten times the base-10 logarithm of the time-mean-square sound pressure, in a stated frequency band (often frequency-weighted), divided by the squared reference sound pressure of 20 µPa, the threshold of human hearing.

$$SPL = 10Lg[p2/ pref2]$$

Where p^2 = time-mean-square sound pressure; and p_{ref}^2 = squared reference sound pressure of 20 µPa.

SPECTRUM - A set of sound pressure levels in component frequency bands, usually one-third octave-bands.

TRANSMISSION LOSS - The reduction in sound level from outside to inside a vehicle due solely to the vehicle shell itself.

Abbreviations and Acronyms

ACRONYM	**DEFINITION**
AAM	Advanced Acoustic Model
ANSI	American National Standards Institute
BTS	Bureau of Transportation Statistics
dBA	Decibels, A-weighted
DOT	U.S. Department of Transportation
ESRI	Environmental Systems Research Institute, Inc.
FRA	Federal Railroad Administration
ft	feet
GCIS	Grade Crossing Inventory System
mph	miles per hour
MUTCD	Manual on Uniform Traffic Control Devices
NARN	North American Rail Network
NPS	National Park Service
NTAD	National Transportation Atlas Database
RD&T	Research, Development and Technology
ROW	right-of-way
SSMs	supplementary safety measures
Volpe	John A. Volpe National Transportation Systems Center
VRUs	vulnerable road users