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In-Vehicle Auditory Alerts Literature Review

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14. ABSTRACT
This literature review covers over 70 documents related to standards, research, and use cases on the design of in-vehicle auditory alerts (IVAAs) for highway-rail grade crossings (HRGCs). Although standards exist for auditory warnings in vehicles and they have been used for years, there are only a few examples of their use at HRGCs. Furthermore, the limited research has concentrated on delivery systems of such messages, not on the specific message that should be provided at the HRGC. The research team recommends that the extensive body of knowledge and standards on IVAAs, identified as part of the review, should be used to design specific ones at the HRGCs for further testing and validation.

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Highway-rail grade crossing, HRGC, in-vehicle auditory alerts, IVAA, auditory alerts, spatial auditory displays, human factors

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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

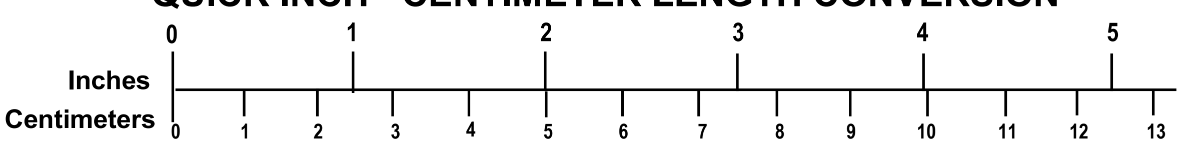
VOLUME (APPROXIMATE)

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

QUICK INCH - CENTIMETER LENGTH CONVERSION



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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Contents

Illustrations

Tables

Executive Summary

Highway-rail grade crossings (HRGCs) present direct and indirect risks to drivers and motorists. To mitigate the risks associated with HRGCs and lower the rate of accidents, various methods can be used to design warning systems that can inform and remind drivers of proper compliance behavior at HRGCs. While HRGCs present motorists with some visual cues and signage on the approach to the crossing, with active crossings also providing auditory feedback, in-vehicle auditory alerts (IVAAs) can offer additional measures to provide multimodal redundancy, improve driver compliance, and reduce the likelihood of an accident. From October 2018 through 2019, the Federal Railroad Administration sponsored Michigan Technological University and Virginia Polytechnic Institute and State University's investigation of related works of knowledge on standards, research, and use cases on the use of auditory alerts to establish guidelines on the design of IVAAs for HRGCs.

Standards relevant to IVAAs were reviewed for this study, including the International Organization for Standardization (ISO) 15006 "Road vehicles — Ergonomic aspects of transport information and control systems — Specifications for in-vehicle auditory presentation," and the National Highway Traffic Safety Administration's (NHTSA) "Human Factors Design Guidance for Driver-Vehicle Interfaces." The ISO standard highlighted key factors of success for IVAAs, such as audibility and safety criticality, as well as parameters to consider when designing for alerts. NHTSA guidelines focused on the design of safety messages, message characteristics, and auditory interface parameters. Both standards provide key parameters for the design of appropriate IVAAs, with the main takeaway being that the perceived urgency (PU) of the HRGC scenarios needs to be evaluated and tested so the alerts align with driver expectations to ensure enhanced compliance. Additionally, military standard "MIL-STD-1472G" was also reviewed and revealed that ISO and NHTSA guidelines comply with broader design standards.

Furthermore, auditory design variables to consider were also determined through literature reviews on studies related to auditory display use for hazardous situations. The four hazard levels of a situation provide important tools to measure the urgency and appropriateness of different alarms, with the HRGC case being less hazardous than an immediate danger case. The literature indicates that determining the type of hazard represented by a HRGC would require user studies and depend on the type of crossing drivers encounter. Consequently, the type of auditory cue and various auditory parameters explored important factors in properly designing an IVAA for HRGCs.

A review of ongoing projects in Greece and the Netherlands show promise in expanding the technology for delivering IVAAs to drivers, with different approaches and redundancies considered. However, they lack fundamental research into the type of warning content of a voice message that should be used. This finding was also supported by our literature review for IVAA applications specifically targeting the rail industry and HRGCs. This review did not produce many results, as research teams have tested the technology for delivering in-vehicle alerts for HRGCs since 1995, but most efforts have targeted the delivery system, and not the message. Several programs have included an auditory component, typically beeps or tones, intended to alert the driver to a train or HRGC location. Nevertheless, there are very few instances where any research is shown into what the auditory message should include. This state of research on auditory display use in a rail context, both in research and practice, confirms the need for a study

on the fundamental effects of different alerts in a HRGC context, which informed the scope of the study to review fields related to HRGCs for relevant variables and criteria.

Literature reviews on auditory displays in non-HRGC related driving contexts provided further recommendations and design guidance for the HRGC scenario. Extensive studies have shown that auditory icons, while highly urgent, can cause high PU in drivers and, in turn, perform incorrect maneuvers and cause a high perceived annoyance (PA). The relationship of PU to PA was emphasized with an ideal IVAA having a PA that can match the PU of the situation. The same relationship has an overarching effect on the design of IVAAs for HRGCs, as the relative low urgency of the situation renders both spearcons and auditory icons as inappropriate IVAA types. The importance of multimodal displays was a salient aspect of the literature in the field. The literature indicates the benefits of multimodality and showed that redundancy should not only be considered on the HRGC warning system, but also within the context of IVAA design with multiple auditory cues. Related research on collision avoidance systems emphasize that lead time is another variable and should be considered for HRGC scenarios, while Take Over Request (TOR) research indicates the possibility of modeling driver response and anticipating the effect of different IVAAs.

Lastly, the use of auditory display in the aviation field was explored. An overview of the literature confirmed that some of the parameters that were considered were also explored and tested within various contexts, such as air traffic control and cockpit design. Additionally, combining more than two auditory cue types received further support, with an emphasis on considering system reliability with lead time when designing alerts.

The conclusions drawn for this review of the relevant body of knowledge for IVAA design in HRGC situations are multi-faceted. Broad standards and studies help in shaping essential design directions, while specific use cases and rail related research indicate different approaches to HRGC warning and compliance-seeking systems. The research team recommends considering all mentioned findings in the design of HRGC IVAAs and exploring avenues for the implementation of mathematical modeling and interconnected vehicles to successfully minimize the risk of railroad crossing collisions.

1. Introduction

Highway-rail grade crossings (HRGCs) create a conflict point between railway and highway traffic, resulting in a risk to highway users. The users are typically warned of the risks either though passive visual cues of the potential danger (e.g., signs, pavement markings), or through active warning devices (e.g., lights, gates, bells). However, using these methods have not eliminated crashes at HRGCs, but have opened the door for other, innovative methods to improve the safety. One alternative method is in-vehicle auditory alerts (IVAAs), which have the potential to offer multimodal redundancy, improve driver compliance, and reduce the likelihood of a crash. This literature review conducted by Michigan Technological University and Virginia Polytechnic Institute and State University, investigated the related body of knowledge on standards, research, and use cases on the use of auditory alerts to establish guidelines on the design of IVAAs for HRGCs.

1.1 Background

Despite the fact that the rail industry has made great strides in reducing accidents at HRGCs, train-vehicle collisions at HRGCs continue to be a major issue in the US and across the world. According to the Federal Railroad Administration (FRA), 2,031 HRGC incidents were reported in 2016, leading to 296 fatalities and 809 injuries. Although less frequent than vehicle-vehicle collisions, a vehicle-train collision is 20 times more deadly, due to the 4,000-to-1 train-to-vehicle mass ratio (Yan, X., Han, L. D., Richards, S., & Millegan, H., 2010). The majority of train-vehicle collisions can be attributed to the drivers' poor judgment and consequent behaviors, such as failure to obey the safety signals displayed. Traditionally, the most common countermeasure for addressing HRGC collisions has been the implementation of active warning devices, but financial considerations limit the number of applications. In addition, a higher percentage of collisions today take place at locations that already have active warning devices implemented.

To stop the recent plateauing trend in safety, experts are looking to complement active warning device implementation with novel warning devices that can be applied to HRGCs with minimal cost. Given that driving is a visually demanding task, multimodal displays, including an audio channel, are recommended to complement the visual resource. Researchers believe IVAAs offer one alternative to remedy many of the human factors issues related to HRGC safety.

As of the time of this literature review, no effort has been made to systematically design/standardize the messages of IVAAs. Even though our previous research identified a specific alert type, further research is still required to validate its effects with diverse variables, including human factors (e.g., other distractors and driver's age) and environmental factors (e.g., road conditions, intersection angle, etc.). The increasing presence of a "quiet zone" in some areas that remove some of the traditional auditory warnings is also evidence for the need of IVAAs (Federal Railroad Administration, 2016). Large-scale implementation of IVAAs might facilitate safer development of future quiet zones.

1.2 Objectives

The primary objective of the review was to explore available literature related to the establishment of and governance standards for vehicle auditory alerts. The research team expanded the search to look for research using IVAAs to alert drivers at HRGCs. Researchers also investigated past research and guidelines for IVAAs in an aviation context.

1.3 Overall Approach

The team used Google Scholar, the Transport Research International Documentation (TRID) database, and Scopus to look for relevant documents. Researchers reviewed industry magazines, and focused on relevant materials produced in the last decade.

1.4 Scope

The project team reviewed literature on HRGC and simulation research, in-vehicle auditory display research and guidelines, and aviation display research. Select interviews took place within the U.S. and agencies from other countries currently involved in projects relevant to the topic. This report summarizes the outcomes of the literature review and interviews.

1.5 Organization of the Report

This report offers an overview of the auditory alert standards from the International Organization for Standardization (ISO), National Highway Traffic Safety Administration (NHTSA), and the US military in Section 2 and Section 3. Section 4 provides a follow up discussion regarding literature with direct links to the rail industry and the HRGC environment, and Section 6 concludes with a discussion of the alerts used in the aviation industry. Section 7 provides a summary of the research conducted, and the lessons learned.

2. Auditory Display Guidelines

Different standards and guidelines exist for the effective design and creation of auditory displays in a driving context. In this report, the research team reviewed international standards (i.e., ISO 15006), National Highway Traffic Safety Administration (i.e., NHTSA guidelines, and military standards [MIL-STD-1472G] for their relevance in designing auditory displays for HRGCs).

2.1 International Standards for Auditory Display Guidelines in Vehicles (ISO 15006)

The ISO specifications for in-vehicle auditory presentation establish several factors of success for auditory signals for driving in ISO 15006, as follows (International Organization for Standardization, 2011):

- Audibility: degree to which an auditory signal can be heard by a person with normal hearing
- Comprehensibility: characteristic of an auditory signal that enables the driver to understand its meaning in the context in which it is provided
- Distinguishability: characteristic of an auditory signal enabling the driver to perceive the differences between it and other audible signals within the driving environment
- Safety criticality: severity of the likely event that can occur if the driver is unable to avoid a specific hazard

Further requirements needed in the design of appropriate HRGC warning signals include appropriateness, redundancy, and compliance as shown in Figure 1. Message simplicity and consistency are additional factors to consider for speech signals.

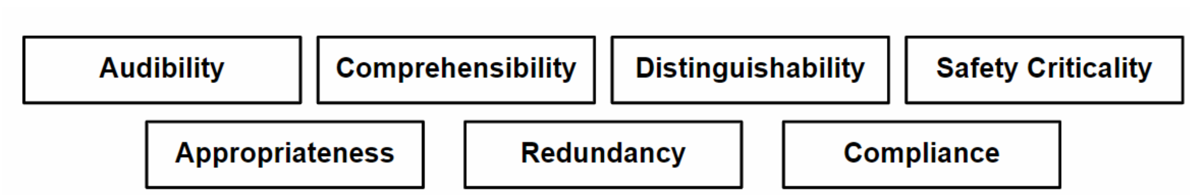

Figure 1 - ISO 15006 IVAA Factors of Success

Frequency component requirements highlighted by the document stipulate that the range for IVAA should lie between 200 and 8,000 Hz to account for age-induced hearing loss in older populations. The frequency of the main audible components should be between 400 and 2,000 Hz, with a broadband or a mix of narrowband signals used to improve driver attention direction and signal location detection.

The ISO also defines a temporal classification of signals according to the expected time for the driver to respond, which is useful for designing signals based on the urgency and action requested from drivers:

- Short term: warnings, critical stop, sudden action required at 0–3 s
- Medium term: informational, advisory, and cautionary at 3–10 s

- Long term: mainly informational and allow enough time for the driver to decide alternatives at >10 s

In the case of long and complex auditory signals, message complexity can help aid drivers by sequencing information in order of relevance or urgency and provide key words relevant to the drive. However, such signals should be limited to five units of information, with more urgent elements conveyed immediately. Any signal containing more units of information needs to be split into smaller alerts.

2.2 NHTSA Auditory Display Guidelines

Several sections concerning auditory display design occur throughout NHTSA's document on "Human Factors Design Guidance for Driver-Vehicle Interfaces" (National Highway Traffic Safety Administration, 2016). NHTSA's design guidance for safety messages, message characteristics, and the auditory interfaces section will be considered for this project.

Design guidance must limit the rate of false or nuisance warnings occurring during a drive. NHTSA standards set an upper limit average of one false warning every 200 miles. Saliency improves with redundancy, so multimodal messages are recommended for urgent alerts and increase the probability the driver can react appropriately to the IVAA. Warning stages should be used with more informational alerts. One and two stage alerts are more appropriate for immediate action and driver behavior change, respectively. The temporal classification of IVAAs by ISO complements this parameter and will be considered when designing scenario-specific IVAAs. Braking stages and perception time are additional temporal factors to consider in the design process.

The ability to quickly capture a driver's attention, especially when presenting simple cues in urgent situations is an important auditory message characteristic. Auditory signals should account for the drivers' comprehension stages and keep messages as simple as possible. Each stage, from extraction through recognition and interpretation, is associated with different parameters of interest, such as urgency cues for interpretation, that should be optimally designed. Signals should follow loudness and audibility requirements. IVAAs should at least be 15 dB above threshold sound levels but no more than 90 dBA, with frequency components between 500 and 2,500 Hz and preferably between 500 and 1,500 Hz. Finally, the document highlights two major parameters relevant to IVAA design: perceived urgency (PU) and perceived annoyance (PA). While the document points out that PA should closely match urgency, PU needs to match the driver's situation at the time of the alert and can be managed through calibrating auditory parameters (e.g., signal pulse rate, tempo, etc.). For speech messages, PA can be reduced by limiting message repetition to no more than three iterations.

2.3 Military Guidelines for Auditory Displays (MIL-STD-1472G)

Military design criteria standards in human engineering include general guidelines for the design of auditory signals, often overlapping the specifications mentioned in both ISO and NHTSA guidelines. Factors such as audibility, discriminability, and compatibility (i.e., appropriateness in ISO 15006), as well as frequency component ranges of 500 to 2,000 Hz and 200 to 5,000 Hz for main and general sound bands are compatible with previous findings (Department of Defense, August 2012). Military guidelines stipulate that speech messages should be presented in a formal and impersonal manner, and that the signal should be repeated until the condition is corrected by the driver. The research team concluded that following ISO and NHTSA guidelines will fulfill military standards as well.

3. Design Variable Considerations for Auditory Display

When the auditory display is designed to alarm/alert the events, the hazard level should be considered. Hazard situations can be divided into four stages from low level 'notice' to high level 'danger' as presented in Figure 2 (American National Standards Institute, 1991). Events at the danger level can directly influence people's status and will result in severe injury or death. At the warning level, the critical events could result in injuries or death. Activities at the caution or notice level may not result in serious injury, but an alarm or alert must still be noticed. The HRGC events could be at the danger or warning levels, therefore, the design variables of IVAAs should be designed considering these hazard levels.

Figure 2 - Four Levels of Hazard a Hazard Situation

3.1 Types of Auditory Cue

The earliest auditory cues consist of a simple sound indicating that something has happened or is about to happen (Sanders, M. S., & McCormick, E. J., 1993) (Sorkin, R., 1988) (Walker, B. N., & Kramer, G., 2004). For example, a long beep sound from a microwave indicates the cooking is complete or a ringing sound from a phone notifies users of an incoming call. This is a simple and effective way to give information but includes limited information, usually binary status. As the effectiveness of display has been confirmed, many researchers have tried to develop sophisticated techniques to precisely convey information depending on context and situation.

3.1.1 Speech

Verbal communication is a basic way to interact with people. Speech cues are easily made by recording human voices or generating synthesized sounds through text-to-speech software. Not only is it possible to convey concrete and precise meanings through the speech interface (Landry, S., Jeon, M., Lautala, P., & Nelson, D., January 2019), it is also relatively easy to create speech sound (Dingler, T., Lindsay, J., & Walker, B. N., 2008). However, speech cues have some weaknesses that should be considered (Dingler, T., Lindsay, J., & Walker, B. N., 2008) (Sanders, M. S., & McCormick, E. J., 1993). First, the presentation rate of speech is slower and reaction to speech takes more time than other auditory displays. Second, as it uses normal human speech to convey information, speech alerts can be easily masked by natural conversation. Finally, speech cues require more mental resources to decode the message. Therefore, caution is necessary when designing a speech interface for a driving or railroad context because these contexts require people to perceive and process information in a very short time. Table 1 presents several design variables and considerations for designing a speech display.

Table 1 - Design Variable for Speech Display and Its Effects on Junam Perception and Performance

Design variables	**Effects on human perception and performance**
Human vs. Synthesized voice	• People are more inclined to prefer 'human speech' than 'machine-like speech' (Muralidharan, L., Visser de, E. J., & Parasuraman, R., 2014).
Voice gender	• The male voice elicited faster and more correct responses than the female voice when performing a visual pursuit tracking task (Arrabito, R., 2009). • Women preferred the male voice of the interactive system and while men preferred the female voice (Moran, S., 2018). The female voice tends to be recognized as higher urgency and carefulness (Hellier, E., Edworthy, J. R., Weedon, B., Walters, K., & Adams, A., 2002) (Barzegar, R. S., & Wogalter, M. S., 1998).
Voice accent	• People prefer accents similar to their own and evaluate a speaker with the same accent as being more knowledgeable (Dahlbäck, N., Wang, Q., Nass, C., & Alwin, J., 2007). • Matching between car voice and driver personality can lead to better driving performance (Jonsson, I.-M., & Dahlbäck, N., 2013). • People tend to perceive warnings presented in a rushed and fast manner as being more urgent and important than those in a monotone and flat style.
Speech style	• Drivers prefer warnings associated with the driving environment over those that blame the driver (Jonsson, I.-M., Nass, C., Endo, J., Reaves, B., Harris, H., Le Ta, J., Chan, N., & Knapp, S., 2004).

3.1.2 Auditory Icon

Auditory icons are short sound clips of parts of existing sounds representing objects, functions, and actions (Gaver, W. W., 1986). For example, a crumbling paper sound when deleting a file in a Microsoft Windows operating system or a camera shutter sound of the smartphone is an auditory icon. Auditory icons are easy to learn and remember and elicit a quick response from users because they use a natural analogy. Auditory icons take advantage of people's prior knowledge or backgrounds about the relationship between sounds and objects/functions (Dingler, T., Lindsay, J., & Walker, B. N., 2008). Furthermore, auditory icons are relatively free from cultural and linguistic barriers (Hemenway, K., 1982). Auditory icons should be naturally connected to real experiences.

3.1.3 Earcon

An earcon is a short, synthetic, musical tone that has an arbitrary relationship with the object or action to which it is referencing (Blattner, M. M., Sumikawa, D. A., & Greenberg, R. M., 1989). Compared to the speech and auditory icons, it is more difficult to catch the meaning of an earcon because it is not a natural sound to which people already are accustomed(Dingler, T., Lindsay, J., & Walker, B. N., 2008). People must be trained to understand, learn, remember, and discriminate the earcon. One example is 'doorbell ringing.' There are no logical relations between the 'Ding-Dong-' sound and a visitor being at the front door. However, once the sound is heard, there is an instant mapping between the two events. Another example is the beep sound from a microwave. When users first hear the beep sound from a microwave, they cannot tell what is going on. However, once they have experience with the microwave, they get to know the meaning of the beep sound. This is the result of the learning process, with or without noticing it.

Although it takes time to get used to an earcon, it is easier to expand the sound family than with auditory icons. Earcons represent an abstract concept by modulating acoustic parameters, such as rhythm, pitch, timbre, register, and dynamic (Brewster, S. A., Wright, P. C., & Edwards, A. D. N., 1992). Using the 'Ding-Dong-' sound, it is easy to generate a new earcon 'Ding-Dong-Deng-' by adding some more sounds. However, an auditory icon, like a camera shutter sound, is a part of the real sound of a real object, and thus, it is not easy to change or extend the existing sound.

Figure 3 illustrates the relative position of auditory alert types depending on semantics and aesthetics. While speech is rather concrete and can convey the exactly intended meanings, earcons have relatively simple semantics in an abstract way. As auditory icons represent real objects or functions, they are in the middle of speech and earcons.

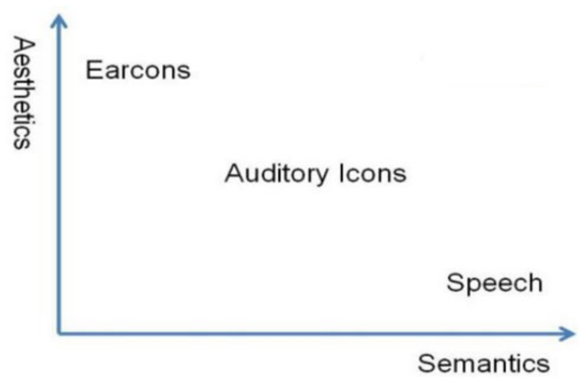

Figure 3 - Relative Position of Auditory Display Types Along Semantics and Aesthetics Axes (Jeon, M., & Sun Y., 2014)

3.1.4 Other Auditory Cues

With the aim of developing effective and efficient interactions, researchers and practitioners have suggested several new types of auditory cues. *Spearcons* are made by compressing spoken words or phrases (Walker, B. N., Nance, A., & Lindsay, J., 2006). They consist of a series of spoken words; however, some spearcons can no longer be comprehensible. Even though people hardly catch the specific words, prior studies reported that they are easy to learn because they derive from the actual speech. A spearcon is a type of hybrid auditory display between speech and non-speech. A *Spindex* uses the first letter of the target word to relate objects/functions to the actual meaning without presenting full words or sentences (Jeon, M., Walker, B. N., & Srivastava, A., 2012). These types of cues are too experimental to utilize in railroad and in-vehicle contexts but may be applied in further research to confirm their validity.

3.2 Acoustic Parameters for IVAAs

Non-speech types of IVAAs can be designed to alert an upcoming urgent event by manipulating the acoustic variables. Different acoustic parameters can have different effects on people's PU of the events (Baldwin, C. L., 2011) (Baldwin, C. L., Eisert, J. L., Garcia, A., Lewis, B., Pratt, S. M., & Gonzalez, C., 2012). Perceived level of urgency is a widely used measure to evaluate the effectiveness of auditory warnings. Therefore, it is important to design the IVAAs to match the PU of the alerts with the situation urgency. This is called urgency mapping (Hellier, E., & Edworthy, J., 1999).

In the driving context, designing the IVAA's acoustic parameters to prevent critical accidents would be the most optimal direction for urgency mapping. Five main acoustic characteristics, presented in Table 2, were found to be effective in alarm categorization (Lewis, B., Eisert, J., & Baldwin, C., December 2014) (Lewis, B. A., Eisert, J. L., & Baldwin, C. L., 2018). Lewis et al. (2018) examined whether the effects of the IVAAs on driving behaviors are different when they optimally or partially meet all five criteria. The researchers conducted a driving simulator experiment with three different groups (i.e., no warning, partially optimized warning, and fully optimized warning) to detect the collision events during a lead vehicle-following task. The drivers with the fully optimized warning condition indicated improved detection performance over the partially optimized warning and no warning conditions. These results showed the importance of considering the essential acoustic parameters when designing IVAAs.

Table 2 - Important Acoustic Parameters and Their Thresholds (Lewis, B., Eisert, J., & Baldwin, C., December 2014) (Lewis, B. A., Eisert, J. L., & Baldwin, C. L., 2018)

Acoustic Parameters	Threshold
Peak-to-total-time ratio (the amount of time a pulse is played at its peak intensity compared to the amount of time the pulse is played in total)	$\geqq 0.70$
Interburst interval	$\leqq 125$ ms

Acoustic Parameters	**Threshold**
No. of harmonics	≧ 3
Base frequency	≧ 1,000 Hz
Pulse duration	≧ 200 ms

3.3 Human Factors Variables for Auditory Displays

Human factors variables must be considered when designing the IVAAs used in a HRGC context. The auditory display system and user (driver) aspects are especially important to consider.

3.3.1 Lead Time

The first consideration when designing an IVAA is how early the system provides a sound cue before the event. The time between the sound provided and the actual event is called *lead time*. The lead time varies depending on the purpose of the auditory display. If the purpose of the auditory system is to call attention to a future event occurring in the next minute, the system provides an auditory alarm a few seconds before the event (e.g., rear collision warning). On the other hand, if the purpose is designed to give feedback on an interaction, the sound is given when users do actions (e.g., crumbling sound when deleting a file in Windows). Researchers reported that the lead time for takeover in highly automated driving must be presented at least 6–7 seconds before the event (Eriksson, A., & Stanton, N. A., 2017). However, research shows that 4 seconds are appropriate for presenting a forward collision warning, in a manual driving context (Wan, J., Wu, C., & Zhang, Y, August 2016).

3.3.2 Spatial Compatibility

Sound has the power to attract people's attention. This can naturally shift one's attention toward a direction where the sound is produced. It means that the system can lead the user's attention toward the direction where a particular event occurs using sound cues. The auditory display is much more powerful than the visual display or tactile display in terms of spatial compatibility because the auditory cue does not need to link the direction of alert provided and an actual event. Previous studies have found that a directional display can elicit a quicker response and better performance in driving and aviation contexts, e.g., (Sanghavi, H., Jeon, M., Nadri, C., Ko, S., Sodnik, J., & Stojmenova, K., 2021), forward collision warning (Yan, X., Zhang, Y., & Ma, L., 2015), or call sign recognition (Kim, S., Miller, M., Rusnock, C., & Elshaw, J., 2018).

3.3.3 System Reliability

Reliability is a basic human factors consideration for all systems. System errors can undermine users' trust. Two representative errors are 'false alarm' and 'miss.' False alarm is the situation when an alarm is provided but an actual event or a signal does not exist. A miss happens when an event or a signal exists, but an alarm is not provided. False alarms can make people turn off the system and missed alarms can make them ignore the system. Chugh et al. (1999) reported the effects of reliability of IVAAs on the drivers' behaviors. Not only did the decrease in reliability reduce the drivers' trust in the system, but it also created a negative effect on driving behaviors. Compared to the non-system alert condition, drivers tended to initiate braking later or earlier after they experienced false alarms or missed signals, respectively.

4. Auditory Display in a Railroad Context

As noted in Section 1.3 the research team used Google Scholar, the TRID database, and Scopus for most of the literature review search. Researchers also reviewed industry magazines relevant to the topic. Although the focus was on materials produced in the last decade, this research also included older relevant materials.

4.1 Rail Industry Literature

The research team reviewed more than 30 papers discussing some aspect of HRGC warnings but found few that addressed in-vehicle alerts for HRGCs. The most closely aligned project to this research program was conducted in Australia (Larue, G. S., Kim, I., Buckley, L., Soole, D., Rakotonirainy, A., Haworth, N., & Ferreira, L., 2014). The Intelligent Transport Systems for Safer Level Crossings program researched a variety of HRGC interventions, and then conducted a simulator experiment that tested responses to auditory messages received by drivers. The auditory alerts were designed using previous work on auditory alerts in other contexts, but it was unclear exactly which standards were used. This research was the only reference that specifically addressed the selection of the warning to be used in vehicles at HRGCs (Landry, S., Jeon, M., Lautala, P., & Nelson, D., January 2019). This paper described early research on the type of warning to use at a HRGC, and the behavior of drivers in response to that warning. The research team found that a voice message along with an auditory cue provided both a warning and instruction in how to address the warning. The warning started with an earcon, "beep-beep" then continued with the voice message "crossing ahead—look left and right." The research showed that using this warning significantly improved the driver behavior response at the HRGCs.

To create a successful in-vehicle alert, a message must first be conveyed to the vehicle from the railroad environment. Many papers focused on techniques for making that connection. In 1995, FRA tested potential systems at the Transportation Technology Center (Carroll, A., Passera, A., & Tingos, I., 2001). Researchers found that while the concept was feasible, the available systems at that time were not adequate to provide a reliable warning signal to a vehicle approaching a HRGC. In 1997 and 1998 the Minnesota Department of Transportation helped develop an in-vehicle signing system intended to help alert bus drivers to both nearby HRGCs and to the presence of a train near the crossing (SRF Consulting Group, Inc., August 1998). An audio tone was used to alert the driver to check the visual output. The system used the existing active HRGC system to detect a train, and transmitted information to the receiver mounted in a school bus when a train was approaching the HGRC. The team found no statistically different behavior from the bus drivers after the system was installed. In 1999 a team from the University of Calgary conducted a driving simulator study testing how driver trust in an in-vehicle system would be affected by the reliability of the system Calgary (Chugh, J. S., & Caird, J. K., 1999).

In 2004, R.F. Benekohal led a team from the University of Illinois in testing an in-vehicle warning system that used a radio transmitter connected to the existing active warning system at 5 HRGCs in the Chicago suburbs to transmit a warning to 300 vehicles from 38 companies that agreed to participate in the test (Aycin, M. F., & Benekohal, R. F., 2002) (Benekohal, R. F. & Aycin, M. F., 2004) (Benekohal, R. F., & Rawls, C. G., 2004) (Benekohal, R.F., & Rawls, C. G., 2004a) (Benekohal, R.F., & Rawls, C. G., 2004b). The system provided both a visual warning and an auditory warning (e.g., a beeping tone) to the drivers. The literature did not describe how the auditory tone was chosen, but reliability issues with this system led participants to question why it was used in locations that already had active traffic control devices.

In 2013, the University of Queensland reported on a driving simulator experiment they conducted comparing two “new” warning techniques (Tey, L.-S., Wallis, G., Cloete, S., & Ferreira, L., 2013). Tey et al. (2013) compared rumble strips with a stop sign, and an IVAA using three voice alerts with standard HRGC warnings, a stop sign with crossbuck, and an active warning system with flashing lights and a clanging bell. The researchers determined that the stopping compliance rates for the IVAA and active system were similar. The research team did not report how they developed the voice message but did note that more work was needed on the message’s wording and timing. More importantly, they found that simulator results were consistent with the field data, indicating that it was valid to use simulators for future research efforts.

In 2019, a team from the University of Alberta developed a probabilistic model for assessing collision risk between trains and highway vehicles in real time that could be used to provide an alert to the vehicle driver (Wang, X., & Li, J., February 2019). Wang et al. (2019) tested the model in Edmonton, AB, using available connected vehicle technologies using dedicated short-range communications. A unit placed on a train communicated with a unit placed in a test vehicle. The system received a signal, determined that a collision might occur, and provided both an auditory and visual alert to the driver. Wang et al. (2019) confirmed that communication between the train and vehicle could happen, and that the warning received in the vehicle allowed the driver to slow and decrease the risk of a collision. Only two tests were reported, however, and there was no discussion of the audio warning used. Another paper mentioned IVAA as an opportunity to improve driver behavior outside of the physical HRGC infrastructure(Salmon, P. M., Lenné, M. G., Read, G., Mulvihill, C. M., Cornelissen, M., Walker, G. H., Young, K. L., Stevens, N., & Stanton, N. A., 2016).

In 2008, FRA published a literature review summarizing the research completed on driver behavior at HRGCs from 1990–2006 (Yeh, M., & Multer, J., 2008). This review reported on topics ranging from responses to existing traffic control devices to warning devices used on locomotives and driver demographics. It also included a section on in-vehicle warning displays. The research available at that time was mostly preliminary in nature, and generally inconclusive. This report provides a detailed bibliography of research available from that time period. Other papers explored driver response time, a critical feature that will be required to determine when or where to apply IVAAs for best effect (Larue, G. S., & Wullems, C., 2019) (Hsu, C. -J. & Jones, E. G., 2017). Larue et al (2019) used a system of pneumatic tubes to develop a HRGC speed profile, Hsu et al. (2017) explored the stopping time required for connected vehicles. Still more research efforts investigated driver response to traffic control devices currently in use (Beanland V., Lenné, M. G., Salmon, P. M., & Stanton, N. A., 2016). Beanland et al. (2016) used a self-reporting survey technique to gather response information from drivers, motorcyclists, bicyclists, and pedestrians and found that road user responses differed from pedestrian results. Another research team performed a specific validation study to compare field and simulator results (Larue, G. S., Wullems, C., Sheldrake, M., & Rakotonirainy, A., July 2018). They monitored driver behavior at a passive HRGC in Brisbane, Australia, for 3 months, and then replicated the HRGC in a driving simulator. Their results indicated that the simulator was a valid research tool in this low traffic passive HRGC scenario. While none of these research efforts dealt with

IVAAs, they provided valuable background information for designing the application of IVAAs for future research efforts.

While reviewing the current literature, the research team found several references to IVAAs used in a highway work zone environment. This environment is similar to the HRGCs. A team from Minnesota investigated the use of a Bluetooth based in-vehicle message system to alert drivers to the presence of construction workers (Liao, C. -F., 2019). Although primarily focused on the Bluetooth delivery system, the team did use the message elements developed in an earlier human factors study (Craig, C. M., Achtemeier, J., Morris, N. L., Tian, D., & Patzer, B., 2017). However, there was no attempt to determine driver response to the message provided. The paper did include this statement, "In the future, there is a need to develop guidelines for engineers and operational staff to select auditory information elements of in-vehicle messages that are compliant with standards." The app can potentially be integrated with the 511 or other navigation apps to receive work zone information statewide.

4.2 Implementations and Pilot Programs

Discussions with industry and academics revealed several domestic and international projects and studies that relate to IVAAs. The following provides a brief summary of two applications.

4.2.1 ProRail, Netherlands

ProRail, an agency tasked to maintain and develop the national railway network in the Netherlands has teamed up with a Dutch application developer, Flitsmeister, to provide IVAAs on approaching HRGCs (Dijkema, E., 2019). Instead of implementing the warnings across all HRGCs in the network, they are only provided to 330 HRGCs deemed "dangerous" by the agency. The smartphone application (see Figure 4) informs drivers about approaching a potentially dangerous HRGC, and about obstructions when the HRGC warning devices have failed. In the future, the objective is to integrate the warnings with traffic flow management, such as predictions of next train arrival, waiting time for the green light, or instructions for alternative routings. Flitsmeister currently has over 1.4 million users and data from participating drivers has been used to compare driver behavior (e.g., speed profiles) between drivers with and without IVAAs at the HRGCs.

Figure 4 - Flitsmeister IVAA Interface in Netherlands

4.2.2 SaferLC Project, European Union

The European Union's multiagency research project "*SAFER Level Crossing by integrating and optimizing road-rail infrastructure management and design*" seeks to improve safety and minimize risks at and around HRGCs (Grau, J. M. S., 2019). The 2019 research from Grau, completed in early 2020, attempted to develop innovative solutions and tools to detect potentially dangerous situations leading to collisions at HRGCs as early as possible and to prevent incidents at HRGCs. It concentrated on both technical solutions and human processes. The project developed a toolbox which integrates all the project results and solutions to help both rail and road managers to improve safety at HRGCs.

The project consortium consists of 17 academic, public and private stakeholders and the research program includes several activities related to IVAAs at HRGCs. The Hellenic Institute of Transport has been leading a pilot study in Greece where static and dynamic alerts of HRGCs and approaching trains, respectively, are provided to 530 taxi vehicles as they enter the limits of 29 geofenced HRGCs. The warning includes visual and auditory components and it runs as a mobile component on top of the dispatcher application. When a train is approaching (i.e., within 60 seconds), a countdown to train arrival is provided (see Figure 5). The research concentrates on technical capabilities for providing the warnings, but analysis of driver reactions and behavior before and after.

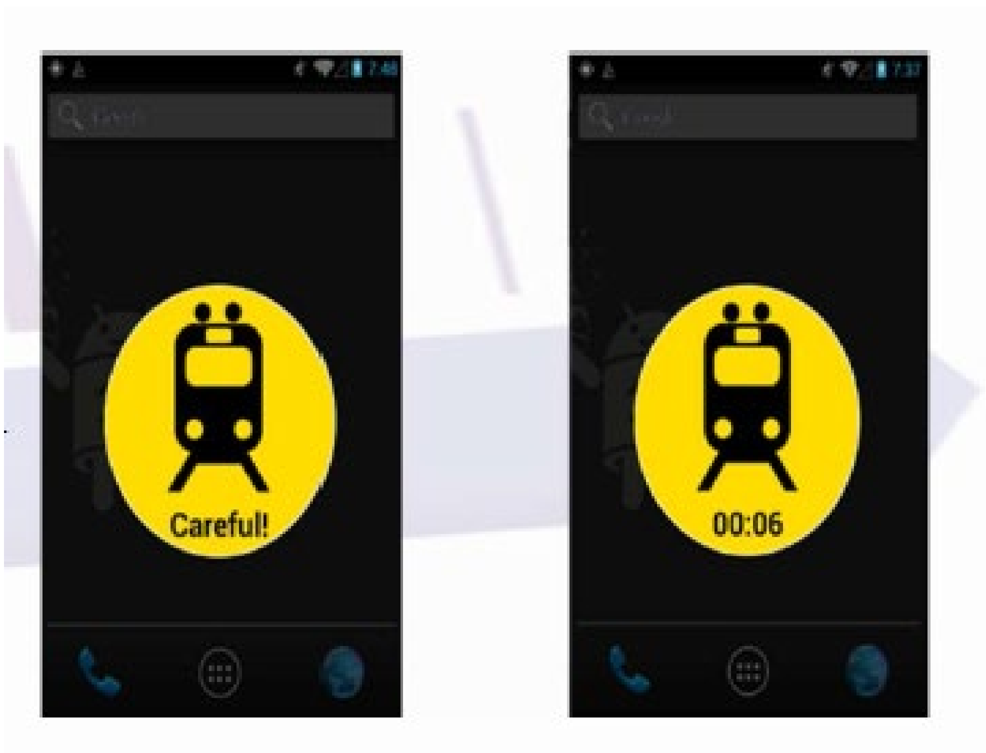

Figure 5 - IVAA Warning in Greek Pilot Study

Three SAFER-LC consortium members are evaluating the impacts of various safety-related improvements in simulated settings as part of the project, but most of the improvements can be categorized as physical safety enhancements at HRGCs. The exception is analysis by Société nationale des chemins de fer français (SNCF) (France) to evaluate the impacts of "proximity messages" via in-vehicle device, where drivers were provided with dashboard messages (i.e., with audio supplement) warning about approaching danger (i.e., HRGC was one of the three danger types). The vehicle's speed and other driver behavior parameters were measured as main outcomes.

4.2.3 Waze and Norfolk Southern Railroad Collaboration

Domestically, Waze, a Global Positioning System navigation application, partnered with Norfolk Southern Railroad to increase driver awareness around HRGCs. Waze creates a geofence around selected HRGCs and provides a visual informational message (Figure 6) to the drivers if they stop within one of the geofenced areas. The main emphasis is to increase awareness of the HRGCs; no specific warning is provided

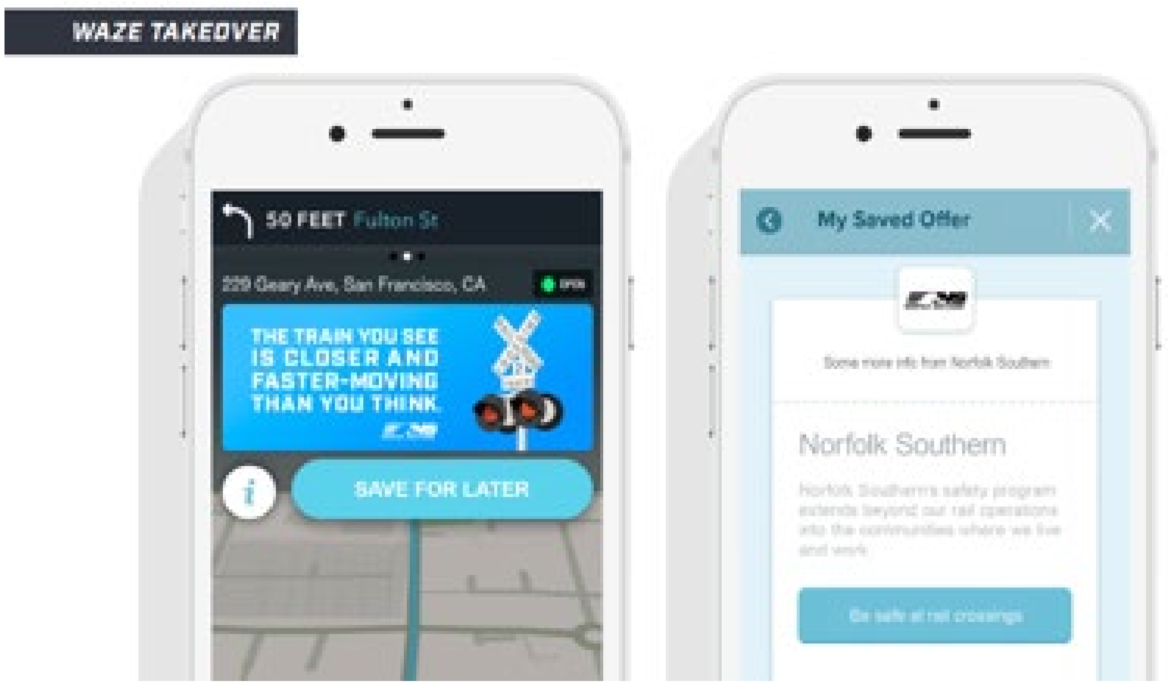

Figure 6 - Screenshot of Waze Warning (courtesy of Norfolk Southern Railroad)

5. Auditory Displays in Driving Context

With the ubiquity of vehicle user interactions in the automotive industry, much research has been conducted on the design of appropriate auditory displays in various situations. As previously asserted by NHTSA guidelines (National Highway Traffic Safety Administration, 2016), auditory messages are capable of quickly grabbing a driver's attention. This greatly aids drivers in properly reacting to road conditions and obstacles in time, and the design of optimized IVAA for different situations has been the focus of most research in the field. Additionally, prior research exists on the design of IVAAs for HRGC contexts. Thus, reviewing all available and reputable research in the field will further the goals of this project by indicating ineffective configurations as well as promising leads to the design of auditory displays for HRGC scenarios.

The following sections will discuss prior research findings relevant to the project.

5.1 Auditory Icons

Initial research on the use of auditory icons in driving revealed significantly improved driver performance for both front-to-rear and side collisions (Graham, R., 1999) (Belz, S. M., Robinson, G. S., & Casali, J. G., 1999). Research findings indicate auditory icons can enable drivers to quickly react to impending situations (Graham, R., 1999), as well as correctly identify them (Belz, S. M., Robinson, G. S., & Casali, J. G., 1999). Additionally, further research suggested that both emotional response and brake reaction can be significantly improved when using auditory icons instead of earcons, especially in more urgent situations (Larsson, P., Opperud, A., Fredriksson, K., & Västfjäll, D., 2009).

Limitations on the use of auditory icons severely limit their inclusion in IVAA systems. Studies on auditory icons have also shown that drivers are led to more inappropriate responses when responding to auditory icons (Graham, R., 1999). This can be explained by the high urgency auditory icons (Graham, R., 1999), causing a startle response and being inflexible for use in situations with varying urgency levels (Nees, M. A., & Walker, B. N., 2011). Another limitation rests in the potential for the auditory icon to not be perceived correctly in an actual driving environment, where road sounds and masking can occur and impair a driver's ability to recognize the icon as an IVAA (Belz, S. M., Robinson, G. S., & Casali, J. G., 1999). The quick response time and high recognizability of auditory icons in simulator studies can then be explained in part to the highly urgent alerts triggering participants to respond in a riskier manner, manifesting into a higher rate of false-positive responses which can erode driver trust. These findings are considered in NHTSA guidelines, which inform designers to avoid using auditory icons for bus and heavy vehicles where startled or panicked responses could lead to disastrous consequences.

The literature on the use of auditory icons in a driving context indicates that, while auditory icons can be beneficial for highly urgent situations, they should be avoided due to their salient disadvantages.

5.2 Speech and Spearcons

Literature on the use of speech-based messages in driving scenarios has shown that speech and spearcon cues can form the basis for enhanced menu navigation cues (Jeon, M., Davison, B. K., Nees, M. A., Wilson, J., & Walker, B. N., 2009) (Jeon, M., Gable, T. M., Davison, B. K., Nees,

M. A., Wilson, J., & Walker, B. N., 2015) (Walker, B. N., Lindsay, J., Nance, A., Nakano, Y., Palladino, D. K., Dingler, T., & Jeon, M., 2013). Additionally, speech alerts for alerted events in a video simulated self-driving car context resulted in higher level 1 situation awareness (Nees, M., Helbein, B., & Porter, A., 2016). Spearcons can also efficiently reduce driver distraction, whereas earcons are not as effective in that goal (Larsson, P., & Niemand, M., 2015). Nevertheless, several issues with the use of speech messages and spearcons exist. First, high perceived annoyance (PA) can take place (Nees, M., Helbein, B., & Porter, A., 2016), especially as speech messages are repeated (National Highway Traffic Safety Administration, 2016), or a conversation involving the driver is occurring (Nees, M. A., & Walker, B. N., 2011). Spearcons may only provide marginally better performance in some cases (Jeon, M., Davison, B. K., Nees, M. A., Wilson, J., & Walker, B. N., 2009), with similar PA concerns. Thus, speech-based messages will be considered in this project, but their limitations will be considered in design.

5.3 Alarm Reliability and Sensitivity

Research on IVAA reliability and sensitivity has shown that reliability plays a large role in determining driver performance and trust (Bliss, J. P., & Acton, S. A., 2003). An interesting finding in some studies is that less reliable alarms lead to the least collisions (Bliss, J. P., & Acton, S. A., 2003). This can be explained by related studies on in-vehicle collision avoidance warning systems (IVCAWS) running the risk of conditioning the driver to overly rely on the system and make more mistakes (Maltz & Shinar, 2007; Ruscio, Ciceri, & Biassoni, 2015). In cases where the system fails to detect danger, drivers are more likely to slow down in low reliability systems than in both high and medium reliability systems (Maltz, M., & Shinar, D., 2004). However, low reliability could lead to driver mistrust in the system (Bliss, J. P., & Acton, S. A., 2003), especially in the case of aggressive drivers, who are much more likely to turn off the system due to its low reliability and not benefit from any of the previously mentioned effects (Jamson, A. H., Lai, F. C. H., & Carsten, O. M. J., 2008).

In general, IVCAWS studies have shown that drivers tend to overestimate their headway, making collision warning systems useful for short and long-term driver compliance (Ben-Yaacov, A., Maltz, M., & Shinar, D., 2005). Following the ratio of one false/nuisance warning every 200 miles indicated in NHTSA guidelines (National Highway Traffic Safety Administration, 2016), the research team believes that alarm sensitivity is an essential factor to modulate and evaluate in various HRGC scenarios. There is an expectation to design a highly sensitive, conservative alarm, which conditions users to comply to proper HRGC behavior. This is supported by previous research conducted by the research team, as an IVAA helped remind drivers of dangers and proper compliance procedures near obstacles (Landry, S., Jeon, M., Lautala, P., & Nelson, D., 2016).

5.4 Collision Avoidance System Parameters

Additional parameters and techniques used for collision avoidance systems have been evaluated in driving research. Demographic information should be considered, as studies have shown older trained drivers react quicker to unexpected events with auditory alerts, while other groups only significantly benefit for expected events (Porter, M. M., Irani, P., & Mondor, T. A., January 2008).

Sound manipulation techniques can also improve driving performance. Looming (i.e., increasing intensity of alarm over time) (Gray, R., 2011), radio sound level manipulation (Fagerlönn, J., Lindberg, S., & Sirkka, A., 2012), and proper timing for alerts (Winkler, S., Werneke, J., & Vollrath, M., 2016) can significantly reduce brake reaction time for drivers. Lastly, balancing loudness with semantics can help driver performance (Baldwin, C. L., & May, J. F., 2011), with a trade-off between PU and PA requiring urgency coding through pulse rates and other parameters (Gonzalez, C., Lewis, B. A., Roberts, D. M., Pratt, S. M., & Baldwin, C. L., 2012) (Baldwin, C. L., Eisert, J. L., Garcia, A., Lewis, B., Pratt, S. M., & Gonzalez, C., 2012).

PA is a major factor in IVAA design, needing as much focus as PU due to its effect on appropriateness (Marshall, D. C., Lee, J. D., & Austria, P. A., February 2007). As found in previous research on auditory icons, IVAAs (Nees, M. A., & Walker, B. N., 2011), and alarm reliability (Jamson, A. H., Lai, F. C. H., & Carsten, O. M. J., 2008), PA can cause initially perceived great IVAAs not to be chosen, mainly due to PA causing an erosion of driver trust.

Spatial compatibility is another parameter of interest for auditory displays. Research has shown that spatial auditory displays can improve driving behavior and performance (Liu, Yung Ching, & Jhuang, J. W., 2012), as well as reduce collisions at intersections (Bella, F., & Silvestri, M., 2017), especially for speech-based messages. Including the direction of threat and obstacles in the IVAA can thus help further inform drivers. However, some limitations exist, with hybrid displays being required when including spatial compatibility (Liu, Yung Ching, & Jhuang, J. W., 2012). This can be explained in part due to drivers requiring additional time and mental effort in verifying threat location in absence of a visual display confirming the threat. As driver compliance to proper rail HRGC scenarios is required in this project, spatial compatibility will not be included in the design of IVAAs.

Another important factor for IVAAs is lead time, which has been the object of multiple studies, especially recently for Take Over Requests (TOR) (Eriksson, A., & Stanton, N. A., 2017). From early research on TORs, lead time variations caused significant differences in driver response and performance (Gold, C., Damböck, D., Lorenz, L., & Bengler, K., 2013), and led to different studies determining dissimilar lead times to be considered (Wan, J., Wu, C., & Zhang, Y, August 2016). As a result, appropriate lead times should be considered and evaluated for HRGC scenarios to give drivers enough time to respond and comply to the HRGC.

As discovered in spatial compatibility studies, multimodality is essential in IVAA systems. Studies indicate that the use of multiple modalities significantly improves task performance in driving situations (Cao, Y., Mahr, A., Castronovo, S., Theune, M., Stahl, C., & Müller, C. A., 2010) (Ho, C., Reed, N., & Spence, C., 2007) (Houtenbos, M., de Winter, J. C. F., Hale, A. R., Wieringa, P. A., & Hagenzieker, M. P., 2017) (Jeon, M., 2019) (Liu, Y. C., 2001) (Politis, I., Brewster, S. A., & Pollick, F. E., 2015), especially in highly urgent situations. Multimodality can also manifest by the combined use of multiple auditory displays, such as speech and earcons (Vargas, M. L. M., Anderson, S., July 2003). However, the different appropriateness of auditory displays (e.g., earcon, spearcon, etc.) makes redundant auditory types situational and likely to cause temporal conflict (McKeown, D., July 2005) (McKeown, D., & Isherwood, S., June 2007) (Wiese, E., & Lee, J. D., August 2004). As PU of HRGC scenarios is different than the one found in collision avoidance systems, the need for a multimodal display needs to be evaluated in terms of perceived appropriateness and annoyance, among other factors.

5.5 Collision Avoidance at Intersections

Collision avoidance scenarios at intersections are of particular interest to this project, as research on this driving situation is similar to that encountered at HRGCs. Past research emphasizes the role of concurrent audiovisual feedback at intersections, providing drivers with enough time to react (Houtenbos, M., de Winter, J. C. F., Hale, A. R., Wieringa, P. A., & Hagenzieker, M. P., 2017). Additionally, early warning signals were rated higher and more useful by drivers and had a positive effect on reaction time, with further studies pointing to a lead time of 4 to 4.5 seconds for red light intersections (Werneke, J., & Vollrath, M., January 2013) (Wan, J., Wu, C., & Zhang, Y, August 2016) (Yan, X., Zhang, Y., & Ma, L., 2015). An important recurring aspect for studies on collision avoidance at intersections is the importance of giving drivers enough time to react to the intersection situation, which further reinforces the importance of lead time as a parameter of interest in this project.

5.6 TOR

TORs research is important to consider in this project due to its relevant findings as well as the gradual adoption and introduction of more automated vehicles in road environments (Melcher, V., Rauh, S., Diederichs, F., Widlroither, & Bauer, W., 2015). While lead time is a crucial factor in TOR studies (Gold, C., Damböck, D., Lorenz, L., & Bengler, K., 2013), other findings are useful for the design of appropriate IVAAs in HRGC scenarios.

Research on TOR modalities shows that multimodal displays using speech or earcons as the auditory display type increase driving performance and trust (Hester, M., Lee, K., & Dyre, B. P., 2017) (Jeon, M., 2019). However, more work is needed as other non-speech alerts with high frequency and fast repetitions might be best for attracting driver attention and promote compliance to proper behavior in TOR situations (Kutchek, K., & Jeon, M., May 2019). This further reinforces the need to evaluate different auditory display types, as HRGC scenarios are distinct from other driving situations and require a re-evaluation of auditory display types appropriate for the scenarios and the urgency level.

TOR research has also revealed new possibilities for the analysis and estimation of driving behavior and performance based on driver characteristics. Driver gaze profile, which can be divided into high, medium, or low risk depending on the frequency with which drivers gaze into meaningful areas of the driving scene (i.e., gaze in front on the road, not to the sides), was found to play a large role in TOR reaction and time spent to react to auditory displays (Zeeb, K., Buchner, A., & Schrauf, M., March 2015). Additionally, this information can be used to create mathematical models of the effects of auditory displays in TORs on the drivers' behavior in autonomous vehicles (Ko, S., Zhang, Y., & Jeon, M., September 2019). This lends credence to the possibility of modeling driver behavior and performance at HRGCs using simulator data, with the potential of using the model as an additional way to pre-select appropriate auditory displays before driver studies occur.

6. Auditory Display in Aviation Context

In the context of aviation, pilots have flown planes with automated systems for decades. As a result, there have been many studies on the development and design of the auditory displays used to present alerts for emergency events in terms of human factors and human-machine interactions. The research team reviewed the aviation literature related to factors that could be considered in this project, i.e., type of auditory cues, acoustic variables, spatial compatibility, and system reliability.

6.1 Type of Auditory Cues

In the aviation context, several studies have tested the benefits of each type of auditory cues. Morris & Leung (1999) investigated the effectiveness of synthesized voice, earcons, and hybrid warnings in terms of reaction time, error, and learnability in the context of aircraft cockpit. Results indicated that alerts including verbal expressions are superior to earcons. Voice alerts took much less time to learn and demonstrated faster response time and fewer errors than other conditions. Smith et al. (2004) and Perry et al. (2007) reported similar results. Smith et al. (2004) conducted two experiments to investigate the ease of learning, retention of information and responsiveness of auditory warnings (e.g., speech, auditory icons, and abstract sounds). In the first experiment, participants first heard eight auditory information warnings with three different types. They practiced with these warnings to develop a memory and were tested 2 and 7 days later. The results showed that the speech and auditory icons were much easier to learn and retain than the abstract sounds, even a few days later. A simulated tracking task with auditory warnings was performed to examine responsiveness and workload in the second experiment. Participants showed the best performance in terms of reaction time and the number of correct responses in the speech condition, followed by the auditory icon and abstract sounds. The information provided previously addressed the advantages and disadvantages of each type of auditory cues tied to the actual task context. Therefore, when considering the characteristics of the in-vehicle context, selecting a proper type of auditory cue for the alert is an important consideration.

6.2 Acoustic Parameters

In safety-related task contexts, such as aviation and driving, the perceived level of urgency should be aligned with the hazard level of the event. Arrabito et al. (2004) found that the urgency levels for some non-verbal auditory alarms used in the 'Canadian Forces CH-146 Griffon helicopter' are perceived as more critical than the actual situation warrants. An alarm named 'Selcal' is used for an incoming call on the high-frequency radio. This situation itself is not a high-level of urgency. However, the alarm, consisting of high-pitched sound with two alternating tones and a 'telephone ring,' made pilots very cautious about the situation.

6.3 Spatial Compatibility

Spatially compatible sound has been tested in the aviation context over many years. Pilots must perceive and respond to three-dimensional information. This suggests that a spatially compatible auditory display may be more useful in this context. Bronkhorst et al. (1996) reported that participants showed better results (i.e., shorter reaction time and lower workload score) when they performed a target tracking task with a three-dimensional auditory display than with no display or even a visual display. The literature reports the benefits of spatially compatible auditory displays to detect or track emergent events or situations (Haas, E. C., 1998) (Simpson, B. D., Brungart, D. S., Gilkey, R. H., & McKinley, R. L., 2005). However, the effectiveness is decreased when the directional sound for alerting the situation is from front/back dimensions (Blauert, J., 1996). Therefore, it would be better to use directional warnings for left/right-sided events.

6.4 System Reliability

The National Transportation Safety Board reported "controllers repeatedly cited the number of unwarranted 'nuisance alarms' that they are exposed to on a routine basis" and "alarms that go off too frequently, especially false alarms" (National Transportation Safety Board, 2006). The excessive and unwanted alarms can be led to distrust and with controllers turning off or ignoring the system. Therefore, the "cry wolf" effect has a highly causal relation to the system reliability. Wickens et al. (2009) explored the "cry wolf" effect in the context of air traffic control. Aircraft tracking tasks using an alert system were observed and analyzed to identify the effects of true and false alerts. As the false alarm rate increased, the participants tended to ignore the alarms.

7. Conclusion

FRA sponsored Michigan Technological University and Virginia Polytechnic Institute and State University in reviewing literature, design standards, and other sources related to the design of HRGC warning systems, particularly in the area of IVAA display design. Research on IVAAs in the rail industry was limited, with most of the work to date focused on delivering a warning message to highway vehicles. Researchers found very limited work on the actual message that should be provided, or in driver response to the IVAAs that were tested. Other areas were of interest, including industry standards used in the highway connected vehicle realm, warnings used in the aviation industry, and general research into auditory warnings, to inform FRA's ongoing work.

The present research suggests the use of auditory icons and spearcons should be avoided, with the concurrent use of other auditory modalities as a preferred approach. IVAA designers should focus on key IVAA parameters such as lead time, system reliability, PA, and PU when creating auditory alerts. Designers should also carefully consider the interconnected nature of these parameters, as can be shown by extensive studies and literature in the automotive and aviation fields. Further studies should be conducted to assess appropriate hazards and urgency levels for HRGC situations. Further applied research should consider novel approaches in HRGC safety and use of mathematical modeling of IVAA designs.

This literature review highlights design guidelines, considerations, and standards related to the appropriate design of HRGC warning systems, particularly in auditory display design. The research team conducted a broad review of standards, research studies, and existing approaches related to auditory warnings, particularly those applicable to HRGC.

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Abbreviations and Acronyms

ACRONYMS	EXPLANATION
FRA	Federal Railroad Administration
HRGC	Highway-rail Grade Crossings
ISO	International Organization for Standardization
IVAA	In-Vehicle Auditory Alerts
IVCAWS	In-Vehicle Collision Avoidance Warning Systems
NHTSA	National Highway Traffic Safety Administration
PA	Perceived Annoyance
PU	Perceived Urgency
SNCF	Société nationale des chemins de fer français
TOR	Take Over Request
TRID	Transport Research International Documentation