# Factors reducing the detectability of train horns by road users: a laboratory study

Grégoire S. Larue[1,2], Christopher N. Watling[1,3], Mahrokh Khakzar[1], Danielle Villoresi[1], Sepehr Ghasemi Dehkordi[1,4]

[1]Queensland, Queensland University of Technology (QUT), Centre for Accident Research and Road Safety – Queensland, AUSTRALIA

[2]University of the Sunshine Coast, Road Safety Research Collaboration, AUSTRALIA

[3]University of Southern Queensland, School of Psychology and Wellbeing, AUSTRALIA

[4]Australian Road Research Board, AUSTRALIA

**Corresponding Author**: g.larue@qut.edu.au

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## Abstract

Level crossing safety is a well-researched safety issue worldwide, but little attention has been placed on the safety benefits of using train horns when trains approach level crossings. Given their adverse effects on the health of residents living near rail tracks, it is essential to ensure that the use of train horns is beneficial to safety. The current study sought to determine in a laboratory environment whether road users (N=31) can detect the range of train horns observed in Australia in terms of loudness and duration, using audio recordings from railway crossings. A repeated measures design was used to evaluate the effects of key factors likely to influence the detectability of train horns: visual and auditory distractive tasks, hearing loss and environmental noise (crossing bells). Train horn detectability was assessed based on participants' accuracy and reaction times. This study showed the duration of the train horn had the most significant effect on the detectability of train horns, with short train horns less likely to be detected. The presence of bells at a crossing was the second largest effect on reducing train horn detection. Train horn loudness also affected detectability: faint blasts are less likely to be noticed, while loudest blasts are more likely to be noticed. However, loud horns reduce the ability to detect the side from which the train is approaching, and may result in longer times to detect the train, in the field. The auditory distractive task reduced the train horn detection accuracy and increased reaction time. However, the visual distractive task and medium to severe hearing loss were not found to affect train horn detection. This laboratory study is the first to provide a broad understanding of the factors that affect the detectability of Australian train horns by road users. The findings from this study provide important insights into ways to reduce the use and modify the practice to mitigate the negative effects of train horns while maintaining the safety of road users.

# 1. Introduction

Recent safety improvements at level crossings are largely due to changing driver attitudes and behaviours towards stopping at the crossing and improvements in the cues leading to train detection (Yeh et al., 2016). Railway crossings use multiple layers of cues to ensure the detection of the crossing and trains, train horns being one of them. While level crossing safety research has examined the effects of warning devices on the behaviours of different road user groups, most studies disregarded the effects of train horns. The literature has therefore primarily focused on the negative impacts of train horns, namely residential noise and its effects on the health of people living near rail lines with sleep disturbances and issues such as insomnia (Hardy & Jones, 2006; Micheli & Farné, 2016; Zannin & Bunn, 2014) and decreased land value (Bellinger, 2006).

An observational study conducted in Australia showed that train horns are not always used by train drivers when they approach level crossings, particularly at passive crossings, where road users are not provided with information about the approach of a train (Larue et al., 2021). Further, when sounded, train horn use was variable, redundant and likely to be insufficiently loud at level crossings equipped with crossing bells. Indeed, crossing bells are often as loud as train horns when measured at the crossing, with a potential masking effect. Consequently, it appears critical to specifically investigate the effects of train horns and ensure that they provide safety benefits to road users. Such evidence is important as the road environment has changed in a number of ways since the last studies on train horns: noisier environments, quieter vehicles, the distraction of pedestrians with headsets, and increased train traffic resulting in bells ringing at level crossings for extended periods. It is therefore important to understand whether train horns are audible by road users in all circumstances.

## 1.1 Effectiveness of auditory warnings for road users

Research assessing drivers, motorcyclists, bicyclists, and pedestrians' alertness to varied signals at rail level crossings has found that behaviours and information used differed among road user types (Beanland et al., 2016; Mulvihill et al., 2016). Mulvihill et al. (2016) found that non-motorised road user behaviour was informed most frequently by auditory warnings, while motorists' was principally informed by visual cues. Beanland et al. (2016) supported these findings while noting previous experiences at rail level crossings as an additional key motivator for motorists' decision-making and behaviours. Beanland et al. (2016) also noted that motorists rarely used auditory information at rail level crossings due to experiences of reduced audibility inside a vehicle. Although these studies have considered auditory information related to trains and rail level crossings, the influential auditory information was noted as hearing a train or bells rather than a train horn.

Dolan and Rainey (2005) specifically measured train horn detectability in three vehicles with different interior noise conditions. They found the mean train horn detection threshold was 10 dB below the overall interior noise level. Despite not accounting for concurrent visual and auditory stimuli or other cognitive tasks associated with driving, it does provide insight into why motorists are less likely to attend to auditory warnings (Dolan & Rainey, 2005). These findings on the effect of background noise on auditory warnings for motorists were supported in a more recent study on auditory warnings other than train horns by Šabić et al. (2021), who noted the impact not only on a reduction in recognition but also on perceived urgency of the warning and driver reaction time. Regardless of the type of auditory warning, there is evidence for a reduction in the audibility of auditory warnings in the presence of background noise in vehicles.

However, a simulated driving study using car horns to analyse spatial auditory warnings obtained results that suggest an effective method in gaining motorists' attention is a spatially predictive meaningful auditory warning that can assist visual attention toward a direction (Ho & Spence, 2005). This may imply that where a motorist is presented with an auditory warning, such as a train horn, and a visual warning simultaneously, the motorist may first be alerted by the train horn to attend to visual information to alter decisions and behaviours that could impact safety.

Overall, the literature suggests that decision-making at rail level crossings varies among road users, with non-motorised road users benefiting and relying more on auditory cues to inform decision-making and associated behaviours.

## 1.2 Effects of visual and auditory distraction on the effectiveness of auditory warnings

Inattention and distraction are major contributors to non-fatal and fatal injuries at rail level crossings for drivers (Landry et al., 2016; Sundfør et al., 2019) and pedestrians (Larue et al., 2018). Reviews of pedestrian behaviour studies reveal unsafe walking behaviours and distractions are associated, particularly when distraction involved mobile phone use (Barin et al., 2018; Mwakalonge et al., 2015; Simmons et al., 2020). Increased headset and mobile phone use among pedestrians (Basch et al., 2014) directly limits the audibility of audio safety messages and increases inattention. As auditory warnings aim to increase attention, such distractions are therefore a vital contributor to reducing the effectiveness of such warnings.

This is particularly relevant for pedestrians; a road user group found to rely more on auditory warnings, however, this group has the highest self-reported (Mulvihill et al., 2016) and observed (Larue et al., 2018) rates of non-compliant behaviours at rail level crossings. Despite drivers relying more on visual than audio cues while driving, it is still essential to consider the influence of distraction as it can decrease the ability to attend to audio safety messages. Inattention can lead to errors while driving (Young & Salmon, 2012) and has been shown to increase the probability of driver collision resulting in injury near or at a highway-rail grade crossing by 9.7%- 14.6% (Zhao & Khattak, 2017).

Distraction from various stimuli can potentially contribute to interruptions in visual and auditory attention, leading to cognitive processing disruptions. Raveh and Lavie (2014) found that when required to identify a tone while performing a visual search task with varied perceptual load, the study participant's detection sensitivity of the tone was reduced consistently as perceptual load increased, even when the auditory detection response occurred before the visual search task or was expected. Although Raveh and Lavie (2014) did not specifically consider audio safety messages, their findings demonstrate limitations for shared attention across hearing and vision modalities. Therefore, considering driving can be a demanding task that requires visually attending to a wide range of stimuli; when distraction is present, the perceptual load can increase, limiting the ability to attend to auditory warnings. With the potential for distraction among road users becoming increasingly prevalent (Wundersitz, 2019), there is a growing need to understand how distraction can influence attending to audio messages designed to increase safety behaviours.

## 1.3 Effects of hearing loss on the effectiveness of auditory warnings

Limited capabilities or inability to process auditory information is a consequence of hearing loss that can impact individual behaviour. Road users with hearing loss are more likely to be pedestrians or cyclists (Thorslund et al., 2012), with these road users more likely to rely on auditory warnings at rail level crossings (Beanland et al., 2016; Salmon et al., 2013). When considering the use of train horns as an auditory safety warning mechanism, hearing loss can reduce safety at rail level crossings, with reduced hearing often contributing to greater levels of inattention in road users (Thorslund et al., 2012). Lundälv (2004) outlined cyclists and pedestrians who had moderate hearing loss found it challenging to localise sound and therefore experienced an increased risk of collisions with vehicles. Thorslund et al. (2012) considered drivers and explored the influence of hearing loss on transport safety. They found only minor effects for hearing loss on factors that contribute to inattention while driving. Concerningly, participants who had a higher degree of hearing loss indicated the least concern with the effects of hearing loss on safety.

Although, Ben Jemaa et al. (2018) have suggested that when considering the hearing loss in older adult drivers, hearing impairment in complex situations where multiple cues need attending may reduce driving performance and safety. Additionally, slower response times to auditory warnings have been found in hearing-impaired older drivers. When combined with different in-vehicle background sounds, the importance of an appropriately timed and designed auditory warning needs consideration (Kim et al., 2010). These studies have focused on sirens and other transport-related auditory information rather than specifically train horns. However, the findings could still be applied when considering safety mechanisms at rail level crossings.

## 1.4 Validity of hearing loss simulations

To better understand the impacts of hearing loss in identifying and processing auditory warnings, experimental studies using hearing loss simulators can explore the recognition and interpretation of such warnings at varied levels of hearing loss in a controlled manner. Biswas et al. (2013) validated the use of a hearing impairment simulator to accurately simulate the perception of sounds for those experiencing varying levels of hearing loss. It does need to be noted that the analysis by Biswas et al. (2013) aimed to understand auditory perception and recognition of speech to assist digital content developers. Arguably this focuses on sounds that require a different level of attention than a train horn. Even though this hearing loss simulator analysis focused on speech recognition, it still provides evidence for the validity of hearing loss simulation use in experiments.

A further challenge for those who experience hearing loss is to localise sounds in the presence of background noise, such as at an urban rail level crossing. Another study analysing speech perception in background noise also found the use of a hearing loss simulator to accurately mimic experiences of varied levels of hearing loss (Kim et al., 2011). Although this study once again analysed speech, the impact of background noise had been a primary focus. Despite differences with train horns, such findings are relevant to urban settings, where background noise is present the majority of the time. Further recognition of distant train horns could echo similar challenges for those with hearing loss to detect and use the audible warning to inform behaviour.

## 1.5 Study aim

Given the intended nature of a train horn as a warning mechanism to inform road users of trains and the variability of usage of train horns in Australia, it appears crucial to understand the effectiveness of such warnings to increase road users' safety. This research aimed to evaluate in a laboratory setting whether the range of train horn blasts as recorded in the field could be detected. The study also considered bells ringing (i.e., environmental noise), visual and auditory distraction and hearing loss as factors that could affect such detection.

# 2. Method

## 2.1 Study design

A repeated measures design was used to evaluate the effect of train horn characteristics, environmental noise, distraction, and hearing loss on detecting train horns as used in Australia. The evaluation of these factors focused on the accuracy of the detection and reaction times. The evaluation was conducted through a laboratory study, which consisted of replaying a sequence of train horns and evaluating their detection by participants. The train horns were generated by processing audio records from field observations conducted over fifty railway crossings in Australia (Larue et al., 2021). Sounds were recorded at the level crossing stop line so that participants experience the conditions that they would encounter when they have to decide whether to proceed through the crossing or not.

Three different distraction conditions were evaluated: (1) no distraction (control); (2) visual distraction; and (3) auditory distraction. An additional condition, hearing loss (4), was included to evaluate the effects of a simulated moderate to severe hearing loss. This resulted in a total of four conditions. The order of conditions was counterbalanced between participants.

In each condition, three different train horn loudness were evaluated: (1) average loudness (80 dB); (2) faint (60 dB); and loud (100 dB). Three different train horn durations were also included: (1) average duration (1 s); (2) short (300 ms); and long (5 ). The combination of these two train horn characteristics resulted in nine different train horns.

The environmental condition included the background noise at level crossings (1) without (59 dB) and (2) with bells ringing (77 dB). For each environmental condition, each train horn was replayed twice (once simulating a train coming from the left, once from the right). The order of train horns and environmental conditions were counterbalanced between the four conditions and participants.

### 2.1.1 Detection task

The detection task consisted in responding to each of the replayed train horns as fast as possible in each of the four conditions. A button push was used for the participant to indicate the detection of the train horn. After the detection, participants also reported orally the side they believed the train was coming from.

Four 12.5 minutes audio files were created, one for each condition. Each audio file consisted of four blocks of approximately three minutes. Two of these blocks consisted of background-level crossing sounds without bells; the other two included ringing bells. The order of blocks was counterbalanced between audio files. The nine different train horns (with characteristics described in section 2.1) were played randomly in each block. The time between two consecutive train horns was randomly distributed using a uniform distribution ranging between 15 and 20 seconds (average of 20 seconds).

### 2.1.2 Distractor tasks

A simple reaction time task was used as the distraction task in this study. The current study required a distraction task that sufficiently engaged the participants and represented texting on a phone or listening to a headset. The visual and auditory distractor tasks developed and presented by Larue et al. (2020) were used.

Both tasks were performed on a smartphone. For the visual distractor task, a word was randomly selected from a list of 6 words every 1.5 seconds and displayed on the screen for one second. One word was the target word and appeared 20% of the time, whereas the other five words were equally likely to appear. Participants had to touch the screen for the target word, while they did not for other words.

The auditory task was similar to the visual task, except that the word was not displayed on the screen but played as a sound by the smartphone equipped with earphones.

### 2.1.3 Hearing loss simulation

The National Institute for Occupational Safety and Health (NIOSH) has made substantial contributions to worker well-being through research advancements in multiple areas, including hearing loss prevention (Hugh, 2020). The NIOSH hearing loss simulator is software that mimics hearing loss experience and has been used in the present study to mimic varying degrees of hearing loss (NIOSH, 2010). Considering that hearing loss simulators have been seen to accurately simulate hearing perception for spoken voice, it is assumed that hearing loss simulation can adequately mimic train horn experiences and provide valuable insight.

The medium to severe hearing loss filter from the NIOSH hearing loss simulator was replicated and applied to the audio signals recorded during the field observations reported in Larue et al. (2021). The filter is characterised by a reduction of 10 dB at 500Hz, which gradually increases to 40dB at 4000Hz, before reducing to 30 dB at 6000 Hz and 20 dB over 8000 Hz.

### 2.1.4 Questionnaires

A demographic questionnaire was administered at the outset of the study. The NASA Task Load Index (NASA-TLX; Hart & Staveland, 1987) was administered at the end of each condition to measure subjective workload. The NASA TLX is a multidimensional rating instrument that assesses six dimensions of subjective workload: mental demand, physical demand, temporal demand, performance, effort, and frustration level.

## 2.2 Participants

Participants were healthy adults with normal hearing ability and were aged between 18 and 40. They were recruited from the general public in the Brisbane area, using advertising (flyers) in Brisbane and through the university environment and online forums, posting on notice boards, and snowballing effects. Recruitment was stratified to obtain a participant population with an equal gender split. Thirty-one participants were recruited for this study. Participants were screened to ensure that their hearing ability was at normal levels using an online hearing test. The minimum requirement was for the participant to be within the average range for their age. Ethical clearance was obtained from the QUT Ethics Committee (clearance number 2021000304).

## 2.3 Materials

The Siemens LMS SCADAS XS Handheld Data Acquisition System and the Siemens LMS SCADAS 3D binaural headset replayed sounds recorded at Australian railway level crossings in previous research (Larue et al., 2021). The integrated replay capability provides an easy yet effective way to replay measured sounds with their acoustic quality as recorded in the field. The headphone's bandwidth is 18 Hz-18 kHz (audibility range for humans). The editing and replaying of level crossing and train horn sounds were performed with the Siemens Testlab 2021.1 software.

The push-button used to record participants' detection of train horn sounds was the Logitech Laser Presenter R500, connected to the computer through BlueTooth.

RTmaps 3.4 was used to synchronise the push-button and the audio files.

## 2.4 Procedure

Each testing session took up to 2 hours of the participant's time. The participant attended the university laboratory and before performing the task, they read the Participation Information Sheet and provided signed informed consent.

To ensure the participant met the eligibility criteria to participate in the study, they completed an online hearing test[1] on a tablet while wearing earphones. This test was used to confirm that the participant did not suffer from hearing loss. If the participant was not eligible (when the report stated that the participant 'may have trouble hearing sounds in noisy places'), they were thanked and given a $10 gift card for their time.

If eligible, they then completed a demographics questionnaire on the tablet. Next, they were equipped with the Scadas binaural headset. They were informed about the task they had to complete:

> *This study is about listening to recordings from train stations; it is done over a number of audio recording blocks. Some of the sounds recorded include train horns, ringing bells, and traffic noise. They have a range of loudness, from faint to quite loud. The main task consists of indicating as fast as possible that you have heard a train horn. To do this, use the clicker. Use the hand you would not use when holding a phone. Once you have clicked, verbally report the side you think the train is coming from. I* [the research assistant] *will record your response. When listening to the clips, you need to focus on the black cross in front of you* [this instruction was not relevant when they also did the visual phone task].

They were then instructed about the distractor tasks:

> *Sometimes, you will also use this mobile phone to perform a reaction time task to the best of your ability. You will need to hold the phone in your hand the same as when you normally use your phone. The mobile phone task is a reaction time task and involves tapping on the phone screen (using your thumb) as soon as you first see the word "CAT" on the screen, or tapping on the screen as soon as you hear the word "CAT" in your earphones. But please do not tap on the screen for any other word. Please respond as quickly and as accurately as possible when you see or hear the word "CAT" to the best of your ability.*

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[1] https://knowyournoise.nal.gov.au/hearing-test

They were familiarised with both the train horn detection task and the distractive tasks (separately then together). Participants adjusted the volume of the smartphone to be comfortable based on their preference during their practice of the auditory task. Then, they completed the four conditions. In between blocks, participants were allowed a 5-minute break.

At the end of data collection, participants were given their participation incentive ($50 gift card).

## 2.5 Data Analyses

Engagement with the distraction tasks was first evaluated to ensure that participants were distracted. This evaluation comprised the performance on the distraction task as well as the effects on subjective workload as measured with the NASA-TLX. The evaluation consisted of the percentage of target words correctly detected, reaction times (time taken by the participant to tap the smartphone's screen after the word is displayed or played by the smartphone), and percentage of incorrect detections (non-target words).

The subsequent data analysis focused on the effect of (1) train horn characteristics (sound intensity and duration), (2) environmental noise (presence of bells or not at the crossing) and (3) the distraction factor (no, visual or audio distraction), and (4) hearing loss on the following dependent variables:

- Accuracy of detection of the train horn blasts;
- Reaction time once train horn is replayed; and
- Accuracy in detecting the train approach direction.

Statistical tests were run using Generalised Linear Mixed Models to take into consideration the repeated measures design of this study. Software R version 4.0.3 was used with the MCMCglmm library. Specifically, the outcome measures were modelled using Generalised Linear Mixed Models (GLMMs). An MCMC approach was used to obtain the 95% confidence interval for the accuracy of the detection of the train horns and reaction times.

The findings on the effects of the factors under investigation were extrapolated to 459 train horn blasts recorded in the field and presented in Larue et al. (2021). This analysis provides insights into the likely detection of train horns as used in Australia.

# 3. Results

## 3.1 Demographics

In total, 31 participants (16 females, 13 males, 2 non-binary) with an average age of 28.1 years (SD=6.2; range=18-39) took part in the study. A breakdown of the participants' demographic details are presented in Table 1.

**Table 1: Participants' demographics (N=31)**

| Demographic variable | Frequency (%) |
|---|---:|
| Gender | |
| Male | 13 (41.9) |
| Female | 16 (51.6) |
| Non-binary | 2 (6.5) |
| Can hear train horns from their residence | |

| | |
|---|---|
| Yes | 12 (38.7) |
| No | 19 (61.3) |
| Frequency hearing train horns | |
| Daily | 7 (22.6) |
| 1-2 times each week | 10 (32.3) |
| 1-2 times each month | 6 (19.4) |
| 1-2 times every 6 months | 6 (19.4) |
| Once a year or less | 1 (3.2) |
| Never | 1 (3.2) |

## 3.2 Engagement with the distraction tasks

For the visual distractive task, participants detected 96.1% of the target words, with a mean reaction time of 629 ms (SD=81). Participants erroneously reacted to non-target words only 0.2% of the time. This highlights that participants did engage with the visual distractive task.

For the auditory distractive task, participants detected 88.6% of the target words, with a mean reaction time of 1,097 ms (SD=140). Participants erroneously reacted to non-target words only 0.6% of the time. Participants also engaged with the auditory distractive task.

Both the visual and auditory distractive tasks negatively affected participants' workload (see Table 2). All dimensions of the NASA-TLX were statistically significantly affected, with the auditory task having the most pronounced effect. It has to be noted that the hearing loss condition did not affect the participants' workload.

Overall, participants engaged with visual and auditory distractor tasks in all conditions during the trial. These tasks negatively affected multiple dimensions of workload. Participants were thus distracted as intended.

## 3.3 Train horn detection

### 3.3.1 Accuracy

The reference level of this study – average train horn (80 dB, 1 s) at a level crossing with no bells and a participant not distracted – was almost always detected with a 96.8% detection rate.

Statistical analyses (see Table 3) revealed that some of the factors investigated affected that detection rate. The factor that reduced train horn detection the most was horn duration of 300 ms (t=-1.49, d.f.=4,428, p<.001). Such a train horn duration reduced the detection rate to 82.3%. Then, two factors were found to have effects of similar size: faint train horns at 60 dB (t=-1.03, d.f.=4,428, p<.001) and the presence of ringing bells at the level crossing (t=-1.03, d.f.=4,428, p<.001). These factors result in reductions to 95.2% and 91.9%, respectively. On the other hand, loud train horns at 100 dB resulted in better blast detection (t=0.76, d.f.=4,428, p<.001), with 98.4% detection. Out of the distraction conditions, only the auditory one affected detection rates through a statistically significant reduction (t=0.35, d.f.=4,428, p=.005). The visual distraction did not affect train horn detection performance. The simulated hearing loss also did not affect train horn detection.

The combination of multiple factors has additive effects. For instance, combining all the factors that negatively impact detection – a short (300 ms) and faint (60 dB) train horn at a level crossing with bells ringing and a pedestrian auditorily distracted – results in a 58.1% chance that the pedestrian would not hear the train horn blast. The combined effects of the factors identified as statistically significant have been interpolated and presented in Table 4. The model reported has a marginal $R^2$ of 0.23 and a conditional $R^2$ of 0.42 when mixed effects are considered.

**Table 2: Subjective workload (NASA-TLX) per condition and statistical significance (Generalised Linear Mixed Model)**

| NASA-TLX | Condition | Mean | SD | *t* | *d.f.* | *p-value* |
|---|---|---|---|---|---|---|
| Mental demand | No additional task | 9.02 | 5.82 | | | |
| | Visual distractive task | 12.27 | 5.37 | 3.64 | 91 | <.001 |
| | Auditory distractive task | 13.44 | 4.58 | 4.80 | 91 | <.001 |
| | Reduced hearing | 8.26 | 5.07 | -0.76 | 90 | .274 |
| Physical demand | No additional task | 4.52 | 4.71 | | | |
| | Visual distraction | 6.48 | 4.96 | 1.77 | 91 | .003 |
| | Auditory distraction | 7.23 | 5.80 | 2.51 | 91 | <.001 |
| | Reduced hearing | 4.92 | 5.19 | 0.40 | 90 | .554 |
| Temporal demand | No additional task | 5.53 | 5.10 | | | |
| | Visual distraction | 7.00 | 5.66 | 1.44 | 91 | .015 |
| | Auditory distraction | 7.50 | 6.04 | 1.94 | 91 | .001 |
| | Reduced hearing | 5.60 | 4.80 | 0.06 | 90 | .924 |
| Performance | No additional task | 16.00 | 4.07 | | | |
| | Visual distraction | 14.77 | 3.52 | -1.76 | 91 | .003 |
| | Auditory distraction | 14.13 | 3.34 | -2.40 | 91 | <.001 |
| | Reduced hearing | 17.06 | 2.91 | 1.06 | 90 | .112 |
| Effort | No additional task | 9.42 | 5.87 | | | |
| | Visual distraction | 11.84 | 4.98 | 2.67 | 91 | <.001 |
| | Auditory distraction | 13.34 | 4.65 | 4.17 | 91 | <.001 |
| | Reduced hearing | 8.92 | 5.05 | -0.50 | 90 | .510 |
| Frustration level | No additional task | 6.98 | 5.72 | | | |
| | Visual distraction | 8.19 | 5.53 | 1.76 | 91 | .002 |
| | Auditory distraction | 8.84 | 6.07 | 2.40 | 91 | <.001 |
| | Reduced hearing | 5.89 | 5.15 | -1.10 | 90 | .076 |

**Table 3. Factors statistically affecting train horn detection**

| Variable | *B* | SE B | *95% CI B* | *β* | *t* | *d.f.* | *p* |
|---|---|---|---|---|---|---|---|
| Intercept | 4.03 | 0.25 | 3.66 – 4.82 | 3.45 | 16.28 | 4,428 | <.001 |
| Train horn | | | | | | | |
| Duration | | | | | | | |
| 300ms | -1.49 | 0.12 | -1.73 – -1.27 | -0.70 | -12.90 | 4,428 | <.001 |
| Loudness | | | | | | | |
| 60 dB | -1.03 | 0.13 | -1.25 – -0.79 | -1.03 | -7.93 | 4,428 | <.001 |
| 100 dB | 0.76 | 0.17 | 0.45 – 1.02 | 0.76 | 4.61 | 4,428 | <.001 |
| Level crossing with bells ringing | -1.03 | 0.12 | -1.32 – -0.82 | -1.03 | -8.74 | 4,428 | <.001 |
| Auditory distraction | -0.35 | 0.12 | -0.62 – -0.14 | -0.15 | -2.82 | 4,428 | 0.005 |

### 3.3.2 Reaction times

Participants took on average 1,080 ms to press the push button when they detected a train horn blast. Statistical analyses revealed that the following factors significantly affected this reaction time: train horn loudness and duration, bells ringing at the crossing and auditory distraction. These effects are shown in Table 5. The other factors considered in this study did not affect reaction times.

Specifically, at a 60 dB loudness, train horns were detected 178 ms (t=8.87, d.f.=3,783, p<.001) slower than louder blasts (80 and 100 dB). Reaction times for these train horn blasts were even slower at level crossings with bells ringing, with an additional 175 ms (t=6.51, d.f.=3,783, p<.001) delay. Smaller effects on reaction times were also observed for train horn durations, with reaction times being 98 ms (t=5.53, d.f.=3,783, p<.001) slower for 5 s long blasts. Reaction times were also slower with the auditory distractive task, increasing by 71 ms (t=4.15, d.f.=3,783, p<.001).

**Table 4. Train horn detection accuracy per condition with 95% confidence interval**

| **Background noise** | **Train horn duration** | **Train horn loudness** | **Condition** | **Train horn detection accuracy** | | | **RT[◊] (ms)** | |
|---|---|---|---|---|---|---|---|---|
| | | | | **Obs[†]** | **Modelled[‡]** | | **Mean** | **SD** |
| Level crossing without bells | Short train horn (300 ms) | 80dB | Control | 82.3 | 89.6 | [85.5;93.6] | 950 | 200 |
| | | | Reduced hearing | 79.0 | | | 1,002 | 210 |
| | | | Visual distraction | 87.1 | | | 979 | 164 |
| | | | Auditory distraction | 74.2 | 86.1 | [79.9;89.9] | 1,106 | 241 |
| | | 60dB | Control | 79.0 | 78.2 | [70.2;83.6] | 1,101 | 402 |
| | | | Reduced hearing | 72.6 | | | 1,095 | 224 |
| | | | Visual distraction | 85.5 | | | 1,104 | 248 |
| | | | Auditory distraction | 75.8 | 72.3 | [64.3;80.2] | 1,103 | 199 |
| | | 100dB | Control | 96.8 | 94.5 | [91.6;96.6] | 1,019 | 328 |
| | | | Reduced hearing | 87.1 | | | 1,082 | 395 |
| | | | Visual distraction | 87.1 | | | 1,011 | 227 |
| | | | Auditory distraction | 87.1 | 92.4 | [88.6;95.1] | 1,171 | 264 |
| | | 80dB | Control | 96.8 | 97.2 | [96;98.5] | 1,031 | 225 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Medium train horn (1 s) | | Reduced hearing | 100.0 | | | 1,076 | 246 |
| | | | Visual distraction | 91.9 | | | 1,081 | 286 |
| | | | Auditory distraction | 100.0 | 96.0 | [94.1;97.6] | 1,202 | 313 |
| | | 60dB | Control | 95.2 | 93.0 | [89.9;95.7] | 1,292 | 419 |
| | | | Reduced hearing | 100.0 | | | 1,317 | 406 |
| | | | Visual distraction | 95.2 | | | 1,305 | 441 |
| | | | Auditory distraction | 93.5 | 90.4 | [85.7;93.8] | 1,361 | 313 |
| | | 100dB | Control | 98.4 | 98.6 | [97.9;99.2] | 989 | 221 |
| | | | Reduced hearing | 96.8 | | | 1,092 | 377 |
| | | | Visual distraction | 100.0 | | | 1,004 | 210 |
| | | | Auditory distraction | 95.2 | 98.0 | [96.9;98.8] | 1,149 | 301 |
| | Long train horn (5 s) | 80dB | Control | 98.4 | 97.2 | [96;98.5] | 1,068 | 196 |
| | | | Reduced hearing | 100.0 | | | 1,124 | 262 |
| | | | Visual distraction | 98.4 | | | 1,373 | 1,934 |
| | | | Auditory distraction | 100.0 | 96.0 | [94.1;97.6] | 1,170 | 244 |
| | | 60dB | Control | 100.0 | 93.0 | [89.9;95.7] | 1,309 | 754 |
| | | | Reduced hearing | 95.2 | | | 1,464 | 656 |
| | | | Visual distraction | 95.2 | | | 1,290 | 661 |
| | | | Auditory distraction | 95.2 | 90.4 | [85.7;93.8] | 1,403 | 483 |
| | | 100dB | Control | 100.0 | 98.6 | [97.9;99.2] | 1,152 | 394 |
| | | | Reduced hearing | 100.0 | | | 1,227 | 760 |
| | | | Visual distraction | 100.0 | | | 1,127 | 608 |
| | | | Auditory distraction | 96.8 | 98.0 | [96.9;98.8] | 1,254 | 529 |
| LC with bells ringing | Short train horn (300 ms) | 80dB | Control | 85.5 | 77.9 | [68.9;83.5] | 1,083 | 400 |
| | | | Reduced hearing | 79.0 | | | 1,055 | 325 |
| | | | Visual distraction | 83.9 | | | 1,064 | 212 |
| | | | Auditory distraction | 74.2 | 72.0 | [62.4;79.2] | 1,101 | 214 |
| | | 60dB | Control | 64.5 | 60.5 | [51.4;70.9] | 1,109 | 288 |
| | | | Reduced hearing | 61.3 | | | 1,252 | 449 |
| | | | Visual distraction | 66.1 | | | 1,362 | 942 |
| | | | Auditory distraction | 58.1 | 53.1 | [43.3;64.6] | 1,267 | 306 |
| | | 100dB | Control | 88.7 | 87.1 | [81;91.4] | 1,012 | 232 |
| | | | Reduced hearing | 93.5 | | | 1,094 | 470 |
| | | | Visual distraction | 91.9 | | | 1,049 | 306 |
| | | | Auditory distraction | 85.5 | 82.9 | [76.8;89.2] | 1,125 | 218 |
| | Medium train horn (1 s) | 80dB | Control | 91.9 | 92.9 | [89;95.4] | 1,129 | 415 |
| | | | Reduced hearing | 96.8 | | | 1,088 | 295 |
| | | | Visual distraction | 96.8 | | | 1,144 | 405 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Auditory distraction | 93.5 | 90.3 | [85.5;93.8] | 1,234 | 330 |
| | | 60dB | Control | 72.6 | 84.1 | [78.4;90.1] | 1,382 | 421 |
| | | | Reduced hearing | 71.0 | | | 1,392 | 427 |
| | | | Visual distraction | 69.4 | | | 1,249 | 275 |
| | | | Auditory distraction | 72.6 | 79.3 | [71.8;87.1] | 1,422 | 450 |
| | | 100dB | Control | 93.5 | 96.3 | [94.4;97.9] | 997 | 199 |
| | | | Reduced hearing | 98.4 | | | 1,025 | 200 |
| | | | Visual distraction | 95.2 | | | 1,037 | 216 |
| | | | Auditory distraction | 96.8 | 94.9 | [92.4;97.1] | 1,086 | 216 |
| | Long train horn (5 s) | 80dB | Control | 93.5 | 92.9 | [89;95.4] | 1,130 | 235 |
| | | | Reduced hearing | 93.5 | | | 1,123 | 219 |
| | | | Visual distraction | 93.5 | | | 1,192 | 601 |
| | | | Auditory distraction | 82.3 | 90.3 | [85.5;93.8] | 1,150 | 210 |
| | | 60dB | Control | 77.4 | 84.1 | [78.4;90.1] | 1,824 | 1,285 |
| | | | Reduced hearing | 83.9 | | | 1,498 | 647 |
| | | | Visual distraction | 79.0 | | | 1,543 | 809 |
| | | | Auditory distraction | 85.5 | 79.3 | [71.8;87.1] | 1,767 | 1,157 |
| | | 100dB | Control | 98.4 | 96.3 | [94.4;97.9] | 1,044 | 303 |
| | | | Reduced hearing | 98.4 | | | 1,097 | 387 |
| | | | Visual distraction | 95.2 | | | 1,084 | 396 |
| | | | Auditory distraction | 93.5 | 94.9 | [92.4;97.1] | 1,153 | 284 |

**[†] Observed**
**[‡] Mean and 95% confidence interval**
**[⁰] Reaction Time**

**Table 5. Factors statistically affecting reaction times**

| Variable | *B* | SE B | *95% CI B* | *β* | *t* | *df* | *p* |
|---|---|---|---|---|---|---|---|
| Intercept | 1,080 | 42 | 984 – 1,162 | <.01 | 25.83 | 3,783 | <.001 |
| Train horn | | | | | | | |
| Duration | | | | | | | |
| 5 s | 98 | 18 | 33 – 175 | 0.19 | 5.53 | 3,783 | <.001 |
| Loudness | | | | | | | |
| 60 dB | 178 | 20 | 98 – 256 | 0.23 | 8.87 | 3,783 | <.001 |
| Level crossing with bells and Loudness 60dB | 175 | 27 | 32 – 259 | 0.08 | 6.51 | 3,783 | <.001 |
| Auditory distraction | 71 | 17 | 6 – 131 | 0.06 | 4.15 | 3,783 | <.001 |

## 3.4 Train approach direction detection

When participants heard the reference train horn (1 s at 80 dB), they were 98.4% accurate in reporting the approach side of the train. Statistical analyses (see Table 6) revealed that most of the factors investigated negatively affected that detection rate. The train horn characteristics were the factors that reduced the ability to detect the train approach direction. Faint train horns at 60 dB (t=-7.31, d.f.= 3,984, p<.001), loud train horns at 100 dB (t=-7.38, d.f.= 3,984, p<.001) and long train horns lasting 5 s (t=-8.49, d.f.= 3,984, p<.001) all had an effect of the same magnitude on the detection of the approach direction. Short train horn (300 ms) also reduced accuracy, but to a lower extent (t=-3.60, d.f.= 3,984, p<.001). The auditory distraction task also reduced accuracy a little (t=-3.76, d.f.= 3,984, p<.001), while bells ringing at the crossing was found to slightly increase the detection accuracy (t=3.49, d.f.= 3,984, p<.001). The visual distraction task and the hearing loss simulation did not affect the detection of the train approach side.

As for the detection of the train horn, the combination of multiple factors had additive effects. In the worst case (long and faint train horn while performing the auditory task), the detection accuracy reduces to 79.7%.

**Table 6. Factors statistically affecting the detection of the train approach direction**

| Variable | *B* | SE B | *95% CI B* | *β* | *t* | *d.f.* | *p* |
|---|---|---|---|---|---|---|---|
| Intercept | 5.17 | 0.31 | 4.66 – 5.88 | 5.03 | 16.94 | 3,984 | <.001 |
| Train horn | | | | | | | |
| Duration | | | | | | | |
| 300ms | -0.78 | 0.22 | -1.27 – -0.40 | -0.78 | -3.60 | 3,984 | <.001 |
| 5 s | -1.64 | 0.19 | -2.16 – -1.39 | -1.64 | -8.49 | 3,984 | <.001 |
| Loudness | | | | | | | |
| 60 dB | -1.62 | 0.22 | -2.28 – -1.27 | -1.62 | -7.31 | 3,984 | <.001 |
| 100 dB | -1.61 | 0.22 | -2.15 – -1.23 | -1.62 | -7.38 | 3,984 | <.001 |
| Level crossing with bells ringing | 0.48 | 0.14 | 0.24 – 0.90 | 0.48 | 3.49 | 3,984 | <.001 |
| Auditory distraction | -0.54 | 0.14 | -0.89 – -0.27 | -0.23 | -3.76 | 3,984 | <.001 |

## 3.5 Application to field data

The statistical model for detecting train horns presented in section 3.3.1 has been extrapolated to the 459 train horn blasts from 305 trains recorded during field observations (see Larue et al., 2021 for details). Such an analysis estimates the possible detection of the observed train horn blasts based on factors that affect the likelihood of detection by participants.

On average, our observations of train horns as used in Australia would have been detected 90.3% of the time (89.6% and 94.9% with and without bells ringing, respectively). The detection probability would be reduced to 87.0% if the auditory distractive task were performed. Table 7 provides descriptive statistics of the distribution of the detection rates, considering the background noise at the crossing and auditory distraction.

**Table 7. Estimated rate of detection of train horn blasts as observed at Australian level crossings**

| **Distraction** | **Background sound** | **Detection probability** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Mean** | **SD** | **SEM** | **Min** | **5th percentile** | **median** | **95th percentile** | **Max** |
| No distraction | Level crossing with bells ringing | 89.6% | 6.2% | 0.3% | 61.8% | 79.4% | 90.7% | 96.6% | 97.7% |
| | Level crossing | 94.9% | 2.9% | 0.4% | 88.7% | 89.1% | 95.9% | 98.5% | 98.9% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Auditory distraction | Level crossing with bells ringing | 86.1% | 7.8% | 0.4% | 53.3% | 73.0% | 87.3% | 95.3% | 96.8% |
| | Level crossing | 93.0% | 4.0% | 0.6% | 84.7% | 85.2% | 94.3% | 97.9% | 98.5% |

# 4. Discussion

This laboratory-based study investigated the effects of train horn characteristics (loudness and duration), bells ringing at the crossing, visual and auditory distraction and hearing loss on the detectability of train horns by road users. The analysis focused on the accuracy of the detection of train horns and the direction of the train as well as reaction times.

## 4.1 Detection of train horn blasts

The detection of train horns was very high in this laboratory study. This is an expected result given the loudness of train horns. The study shows that the train horn characteristics (loudness and duration) and the background noise at level crossings can reduce the ability of participants to detect train horns. Short train horns (300 ms long) were the most difficult to detect. Faint train horns (60dB) and bells ringing at the crossing also reduced the detection of train horns. Indeed, bells at level crossings are constantly ringing at approximately 80 dB, and train horns can be partially masked (Larue et al., 2021) and, therefore, less likely to be accurately detected by participants.

This study replayed binaural audio recordings, and it showed that participants were able to detect the side of the train only from auditory cues with high accuracy. However, we found that the train horn characteristics influenced this capability to a large extent. Long, short, loud and faint train horns result in a significantly lower ability to detect the train side without looking for the train. Short and faint train horns are hard to detect, and it is also challenging to extract further information from the auditory cue. For long and loud train horns, the slight difference between what is heard in the left and right ears is too small to be detected by the participant, and they are not able to judge from which side the train is coming. In both cases, an important part of the safety message provided by the train horn is lost, and road users would take longer to know where the train comes from as they would have to switch to visual cues. Bells ringing at the crossing were not found to reduce the ability to detect the train's travel direction from its horn sounds. This suggests that while the bells may mask train horn sounds when their sound intensity is similar to or louder than train horns resulting in reduced detection, bells do not affect the directionality of the warning when detected.

In addition, faint train horns – particularly when bells ring at the crossing – and long train horns increased participants' reaction times. Therefore, such train horns likely require longer times to be detected and may provide less time for road users to react in an emergency. It is unlikely to be an issue for faint train horns as train drivers use such blasts when they aim to follow the rules while reducing noise disturbance rather than warn road users (Naweed et al., 2021) and are therefore unlikely to be used in an emergency. On the other hand, longer train horns are likely to be used in an emergency. This study suggests that using long train horns may have a detrimental effect on the safety of road users. Indeed such a blast would take longer to be detected, and road users would also take longer to identify the side the train is coming from as they would need to look for the train actively. Our findings suggest that train horns longer than a second should not be used, even during emergencies, and that train drivers should be informed and trained to use horns more effectively.

Performance on secondary tasks and self-reported workload show that participants did engage in and were distracted by both the visual and auditory tasks. The auditory distraction task reduced the ability to detect train horns and increased reaction times. However, this was not the case for the secondary visual task in this study. This suggests that the modality of the distraction task is an important factor to consider when evaluating the effectiveness of train horns as a safety warning message. Train horns are auditory warnings, and such warning messages compete with other sounds for access to attention resources from the road user. On the other hand, other types of distractions may not affect the ability to detect the warning as much since such distractions rely on other parts of the attention pool, consistent with the multiple resource theory of attention (Wickens, 1980). This suggests that train horns may not be as effective as intended for road users wearing headphones.

Pedestrians with headphones are a prominent concern for the safety of railway level crossings due to their increased prevalence (Goodman, 2018; Larue et al., 2018; Larue & Watling, 2022) and concerns from the rail industry after multiple fatal collisions (Rail Accident Investigation Branch, 2009, 2010, 2013; Transport Accident Investigation Commission, 2011, 2016). The use of train horns being largely directed at pedestrians (Australian Level Crossing Assessment Model (ALCAM) Technical Committee, 2016) suggests that train horns may not be as effective (in terms of safety) as expected for the most dangerous situations at level crossings. These adverse effects are likely to be worsened by the other auditory warnings at level crossings (bells), which competes for the same attention resources and can even mask train horns. Therefore, when no emergency occurs, train horns may not be necessary at level crossings equipped with flashing lights and bells, particularly when bells are as loud or louder than train horns as heard at level crossings. This also suggests that the approach to improve safety at level crossings by continuously adding layers of controls may not always be the most effective, as such an approach fails to consider the negative impacts of combining safety features. Nevertheless, changes to the use of train horns will require more in-depth investigations, as attempts in other jurisdictions such as the United States (train horn bans) have resulted in increased collisions at level crossings (Zador, 2003). As such, the combining or removal of safety features presents a complicated situation for rail authorities.

Another factor considered in this study was the effect of medium to severe hearing loss and its effects on the capability to detect train horns. Our study did not find any impact of hearing loss on the ability to hear train horns. Hearing loss affects different frequencies at different levels. Spectral analysis of the train horns observed in the field and replayed in this study showed that train horns are characterised largely by lower frequencies, with peaks at or below 750 Hz. On the other hand, the crossing bells (peaks at 2.5 and 3 kHz) and environmental noise were filtered a lot more. Hearing loss tends to affect lower frequencies less (Hornsby et al., 2011), and our hearing loss simulation took that into account, with a limited effect of around 10 dB on train horns, while some higher frequencies were cut by up to 40 dB. Train horns are therefore more easily distinguished from environmental noise. This potentially explains why train horns are not affected by hearing loss in the current study.

## 4.2 Practical Impacts

As observed and replayed in this laboratory study, train horns are blasted to warn of the train's imminent arrival at the level crossing. They are therefore not representative of an emergency event occurring at the crossing. While this study has identified multiple factors reducing the detectability of train horns significantly, train horns as practised in Australia would be detected in the vast majority of cases by road users. Indeed, most train horns are louder than 75 dB and about a second long in duration or longer. Given the negative health effects on residents living near rail lines, there appears to be a number of reductions or changes in the use of train horns that may not impact the safety of railway crossing users. First, a number of train drivers blow their horns multiple times on the approach of level crossings. When no emergency can be foreseen, it does not appear necessary to use the horn multiple times, given that it is highly likely to have been detected the first time. Second, there may be no need to use the louder train horn given that the average train horn at 80 dB is almost always detected, limiting the value of louder train horns to 100 dB, particularly in urban and regional areas. This is also suggested by the loss of directionality of the warning for the louder train horns, making the warning message less informative. Finally, level crossings equipped with all levels of protection (lights, gates, bells) provide such protection independent of the train horn, and rare events at these crossings are unlikely to be related to the road user not being aware of the arrival of a train. This suggests that train horn use at such level crossings could be limited to emergencies rather than every time a train is approaching a crossing.

### 4.3 Strengths, limitations and future directions

Level crossing safety is a well-researched safety issue worldwide, but little attention has been placed on the safety benefits of using train horns at level crossings. Given their adverse effects on the health of residents living near rail tracks, it is essential to ensure that the use of train horns is beneficial to safety. This laboratory study is the first to provide a broad understanding of the factors that affect the detectability of Australian train horns by road users. The findings from this study provide important insights into ways to reduce the use and modify the practice to mitigate the negative effects of train horns while maintaining the safety of road users.

A strength of this laboratory study was to replay binaural sounds as recorded in the field at live level crossings, replicating the sounds with high fidelity and providing information on the direction the replayed sounds came from. The study also considered a number of factors that are likely to result in train horns being missed, providing insights into the most critical factors to consider in future studies.

While the research design employed in this study was comprehensive, there are invariably some limitations to the study that need to be acknowledged.

First, this laboratory study did not involve walking or talking. This provides only information about the ability of participants to hear train horns. Future work should consider whether driving or walking affect the ability to hear train horns. In particular, this study identified that road users may not always be able to identify the side the train is approaching from sound only. Under such conditions, road users would need to rely on visual attention to detect the train. Therefore, it would be valuable for future research to investigate visual perceptions (i.e. whether road users compensate for these degradations by looking for the train), and whether visual distraction interferes with road users' ability to detect the train.

Next, while the train horn records used in this study covered a variety of types of Australian train horns, only a small sample was used. There is a range of train horn devices used, each type of locomotive having a distinctive sound. In particular, the frequency of the train horns was not considered in this study, despite its potential effects on detection. Further research should investigate whether train horn frequency is an important factor to consider.

The effects of hearing loss on detection depend on the hearing loss profile of the observer. A single hearing loss profile was tested in this study. The profile used was mainly characterised by a high-frequency loss, resulting in limited effects as train horns contain principally lower frequencies. This approach limits the ability to generalise the findings on hearing loss, particularly for low-frequency loss. Road users with low-frequency hearing loss may likely have worse detection performance, as our study showed that a reduction of around 20 dB on the typical train horn can lead to an important reduction in detection by participants. Further studies should therefore investigate hearing loss in further detail.

Finally, the detection estimates provided in this study rely on extrapolation. While a large proportion of horns recorded in the field are within the bounds of the values that were used in the model, further studies should be conducted to test whether the assumptions taken (linear interpolations) hold.

## 5. Conclusion

This study has shown that train horn characteristics were found to affect their detectability by participants. Duration has the most significant effect, with short train horns less likely to be detected. Loudness also affects detectability: faint blasts are less likely to be noticed, while loudest blasts are more likely to be noticed. However, loud horns reduce the ability to detect the side of the train from the noise, which may result in longer times to see the train (as they do not know which side to look for the train). When bells are ringing at the crossing, train horns stand out a lot less from the noisy background environment, which results in both lower and slower detection of train horn blasts. The auditory distractive task reduced the train horn detection accuracy and increased reaction time. However, the visual distractive task and medium to severe hearing loss were not found to affect train horn detection.

Overall, this study has shown that average train horns (80 dB) can be easily detected, even in a noisy environment such as when bells ring at level crossings. This suggests that there is no need for train horns to reach 100 dB at the level crossing to ensure the safety of the level crossing, offering opportunities to reduce the effects of train horns on residents living near rail lines.

While the large majority of train horn blasts observed in the field would have been detected by our participants, the combined effects of the different factors considered in this study can result in some train horns being likely to be undetected by a significant proportion of our participants, suggesting the need for further investigations into the safety benefits of train horns.

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