Investigation of the external noise emitted from electric buses in New Zealand and the need for acoustic vehicle alerting systems to improve road user safety

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Glossary

AC-10/AC-14	Asphaltic concrete. The number denominates the largest aggregate size (eg, 10 mm or 14 mm).
ambisonic	Denoting or relating to a high-fidelity audio system that reproduces the directional and acoustic properties of recorded sound using two or more channels.
AVAS	Acoustic vehicle alerting system
A-weighting	The process by which noise levels are corrected to account for the non-linear frequency response of the human ear (refer to L_{A90}, $L_{Aeq(t)}$ and L_{AFmax} below).
dB	Decibel. The unit of sound level. Expressed as a logarithmic ratio of sound pressure P relative to a reference pressure of Pr = 20 μPa (ie, dB = 20 × log(P/Pr)).
dBA	The unit of sound level, which has its frequency characteristics modified by a filter (A-weighted) to approximate the frequency bias of the human ear.
Hz	Hertz is the unit of frequency. One hertz is one cycle per second. One thousand hertz is a kilohertz (kHz).
ICE	Internal combustion engine
km/h	Kilometres per hour
L_{A90}	The A-weighted noise level equalled or exceeded for 90% of the measurement period. This is commonly referred to as the background noise level.
$L_{Aeq(t)}$	The equivalent continuous (time-averaged) A-weighted sound level. This is commonly referred to as the average noise level. The suffix 't' represents the time period to which the noise level relates. For example, '(8 h)' would represent a period of 8 hours, '(15 min)' would represent a period of 15 minutes, and '(2200–0700)' would represent a measurement time between 10 pm and 7 am.
L_{AF}	The A-weighted sound level with fast time weighting.
L_{AFmax}	The A-weighted maximum noise level with fast time weighting. The highest noise level that occurs during the measurement period.
L_{den}	The day/evening/night noise level, which is calculated over a 24-hour period with a: • 5 decibel adjustment applied to the evening period (1800–2200 hours) • 10 decibel adjustment applied to the night-time period (2200–0700 hours).
L_{night}	The night-time noise level, which is calculated from the 8-hour night period (2200–0600 hours) L_{Aeq} averaged over 12 months. No adjustment is applied.
NPSUD	National Policy Statement for Urban Development
target bus	Buses travelling in the direction closest to the participant location, at a steady speed.
UNECE	United Nations Economic Commission for Europe
WHO	World Health Organization

Contents

Executive summary

Reducing sound from the urban environment is good for wellbeing. Electric vehicles have the potential to reduce environmental noise and decrease emissions. Electrifying public transit might drastically benefit cities, as these fleets are continually driving, and diesel bus engines are loud. However, many people rely on vehicle noise for detection. Vehicle detectability affects pedestrians' safety and helps ride-hailing. These issues greatly affect pedestrians with low hearing and low vision in particular. Acoustic vehicle alerting systems (AVASs), which produce noise from electric vehicles so that pedestrians can hear them coming, could make electric vehicles more detectable. This report looks at the need for and applicability of AVASs for electric buses in New Zealand.

A literature review and two studies were carried out to see if AVASs are needed on electric buses in New Zealand.

No studies were found on the detectability of electric buses, or how AVASs improve electric bus detection. Some research was found concerning detection of electric cars and electric trucks. Generally, researchers found electric vehicles are less detectable at speeds lower than 35 km/h, and that pedestrians were more likely to be hit by electric vehicles than by vehicles with internal combustion engines. The quieter vehicle sounds are also known to be a concern for people with low vision or who are blind.

We completed two studies: first, to measure noise differences between electric and diesel buses in New Zealand, and second, to measure people's ability to detect them in urban street environments.

The first study measured the noise made from a diesel bus and an electric bus at three different speeds (10, 30, and 50 km/h). Electric buses were approximately 8 dB quieter than diesel buses in 10 km/h condition, but there was no difference in the 30 km/h condition. Electric buses were slightly louder than diesel buses at 50 km/h.

The second study asked low-vision and non-disabled participants to listen for approaching diesel and electric buses in Auckland and Wellington. We measured how far away the buses were when participants detected them. In Wellington, there was no significant difference between electric bus and diesel bus detection distances or rates. In Auckland, however, participants were more likely to detect a diesel bus than an electric bus, and they detected diesel buses earlier, on average. There was considerable overlap in the data in both cities. The low-vision and non-disabled participants were similar in their ability to detect approaching buses in both cities, but the low-vision participants were significantly less likely to detect a bus early in Auckland than the non-disabled participants.

Before adopting AVASs for all electric buses, more research is needed to understand bus detectability and AVAS efficacy in different New Zealand soundscapes. We recommend both laboratory and field testing of possible AVAS configurations for New Zealand conditions. We also recommend improvements to street infrastructure to promote pedestrian safety as a way to mitigate the effects of bus noise. Adding on-site detectability tools at bus stops such as real-time alerts may help improve bus detection.

Abstract

The purpose of this research was to investigate the differences in noise levels and detectability between electric buses and diesel buses, and to explore the suitability of acoustic vehicle alerting systems (AVASs) for electric buses in New Zealand. The methods included a literature review of bus noise and AVAS issues in New Zealand and overseas; controlled testing to measure the noise levels of diesel and electric buses; and participant testing to measure the frequency and detection distance of different buses on urban streets in Wellington and Auckland. The literature review found that while there are known safety and detectability problems with electric vehicles of all kinds, AVASs are relatively new, and their effects are unclear. Our controlled testing revealed that electric buses are quieter than diesel buses at very low speeds (10 km/h) but there was no difference at 30 km/h, and electric buses were slightly louder than diesel buses at 50 km/h. Our participant testing had mixed results. There were no significant differences in bus detection in Wellington, either by bus type (electric or diesel) or participant impairment status (low-vision or non-impaired). In Auckland, however, participants were more likely to detect a diesel bus than an electric bus, and they detected diesel buses earlier, on average.

Electric buses were less likely than diesel buses to be detected at all, and when they were detected, they were closer to the participant than the diesel buses were. We concluded that further testing is required before deciding whether to introduce AVASs into electric buses in New Zealand. We recommend laboratory testing of potential systems and further street trials to find the most appropriate solution to bus detectability and pedestrian safety, while maintaining the amenity value of the low noise of electric buses.

1 Introduction

Waka Kotahi NZ Transport Agency commissioned MRCagney (NZ) Ltd and Marshall Day Acoustics Ltd to investigate the external noise emitted from electric buses in New Zealand and the need for acoustic vehicle alerting systems (AVAS) to improve road user safety. The research scope included:

- a review of literature concerning the noise of electric buses and its impact on:
  - road user safety
  - the ability of bus passengers to detect an approaching bus
- measurements of the noise of electric and diesel buses in controlled conditions at a range of operating speeds, with a minimum of other streetscape and traffic noise
- measurements of the noise of electric and diesel buses as they approach and pass a location (eg, a bus stop) on different urban streets
- measurement of a sample of pedestrians' ability to detect electric and diesel buses approaching and passing a bus stop on different urban streets
- a research report summarising the literature review and testing and including recommendations about evidence for or against the need for AVASs on electric buses.

We present the research results in four sections.

- Chapter 2 presents the literature about electric buses and noise levels as they relate to pedestrian safety, and bus passenger detection.
- Chapter 3 describes the methods and results for the controlled noise measurements and for the on-street testing with human participants.
- Chapter 4 discusses the implications of the results.
- Chapter 5 makes recommendations about opportunities to promote safety for pedestrians navigating streets where electric buses travel, and for passenger detection of electric buses.

2 Literature review

2.1 Traffic noise: Electric vehicles and internal combustion vehicles

Anthropogenic (human, and human-created) sounds contribute significantly to the ambient soundscape of urban environments. The soundscape is the overall acoustic environment resulting from various individual sound sources. Traffic noise is a key element of urban soundscapes, particularly in heavily trafficked centres. Many inhabitants of urban centres are exposed to high levels of traffic noise, and in many cases, they accept traffic noise as an inherent feature of living in a built-up area (Yamauchi, 2017). However, the World Health Organization (WHO, 2011, 2018) has recognised traffic noise as a key issue that can lead to a range of short-term and long-term health issues, both directly (eg, sleep disturbance) and indirectly (eg, stress).

It is estimated that in western Europe alone, at least 1 million healthy life years are lost each year due to the health effects of traffic noise pollution (WHO, 2011). Accordingly, the WHO provides guideline levels for traffic noise, recommending that daytime levels should not exceed 53 decibels (dB) L_{den} and night-time levels should not exceed 45 dB L_{night} (WHO, 2018).[1]

In recent years, there has been a shift away from vehicles powered by internal combustion engines (ICEs), with increasing adoption of hybrid electric and fully electric powered vehicles. The benefits of electric vehicles are primarily linked to a reduced reliance on fossil fuels, with consequent climate benefits, but electric vehicles also produce lower noise levels than ICE vehicles and therefore provide positive impacts on noise pollution levels. Unlike traditional ICE vehicles, hybrid vehicles in electric mode and fully electric vehicles do not produce idling noise when stationary, and they are also quieter than ICE vehicles while in motion (Pallas et al., 2015).

At low speeds, electric vehicles are notably quieter than ICE vehicles, but at speeds of 50 km/h or more, the sound pressure level of ICE and electric vehicles becomes equivalent as the noise from tyre/road interaction (rolling noise) and wind dominates the overall sound level (see Figure 2.1). The speed at which rolling noise dominates sound emission has been shown to vary with tyre and road surface types, ranging from speeds of 20 to 50 km/h (Pallas et al., 2015; Poveda-Martínez et al., 2017). This relationship has been noted for light and heavy vehicles (Pallas et al., 2014; Pallas et al., 2015; Weiner, 2007). Accordingly, while electric vehicles are quieter than equivalent ICE vehicles at low speed, there is little difference in noise emission when the vehicles are considered across their whole speed range (Pallas et al., 2015).

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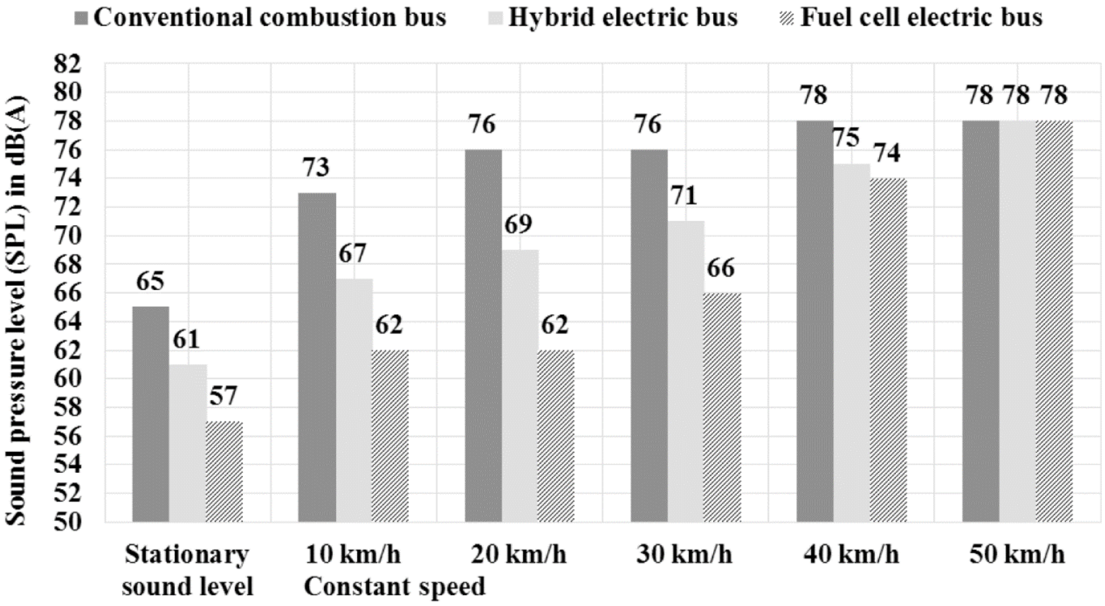
[1] L_{den} is the day/evening/night noise level, which is calculated over a 24-hour period with a 5 dB adjustment applied to the evening period (1800–2200 hours) and a 10 dB adjustment applied to the night-time period (2200–0700 hours). L_{night} is the night-time noise level, which is calculated from the 8-hour night period (2200–0600 hours) equivalent continuous (time-averaged) A-weighted sound level (L_{Aeq}) averaged over 12 months. No adjustment is applied.

Figure 2.1 **The sound pressure levels measured at 7.5 metres for stationary buses, and controlled-speed bus passes, for buses powered by ICEs, hybrid electric engines, and fuel cell electric engines.**



Source: Reprinted from Laib, 2019, p. 380.

To positively impact the overall noise level of traffic, electric vehicles must make up a significant proportion (more than half) of the total traffic (Laib, 2019; Pallas, 2014a; Pallas et al., 2015). In some dense urban centres overseas, street traffic is limited to only public transport or taxi traffic. Accordingly, switching these vehicles over to electric powertrains may have the most significant impact on city centre noise levels, especially given that city centre roads are more likely than roads further away to have low speed limits, which would match to the speeds at which electric vehicles are quieter than ICE vehicles.

Additionally, vehicles in urban surroundings, especially buses, spend much of their time accelerating or decelerating. These speed changes are another factor that puts engine noise to the fore, which would be reduced by changing to an electric fleet. Unfortunately, most studies use constant speed testing for noise, so these benefits are unstudied.

2.2 The benefits of quiet buses: Noise pollution

Electric buses have been acknowledged to produce lower noise levels at lower (city) speeds both internally and externally, and their benefits for urban noise environments are being embraced worldwide (eg, South America (Movés Uruguay, 2019), North America (Sengupta, 2021), Europe (Laib, 2019), Asia (Lee, 2017) and Australasia (Greater Auckland, 2018). Global efforts to reduce overall noise levels from traffic help countries work towards the WHO traffic noise level guidelines outlined in section 2.1.

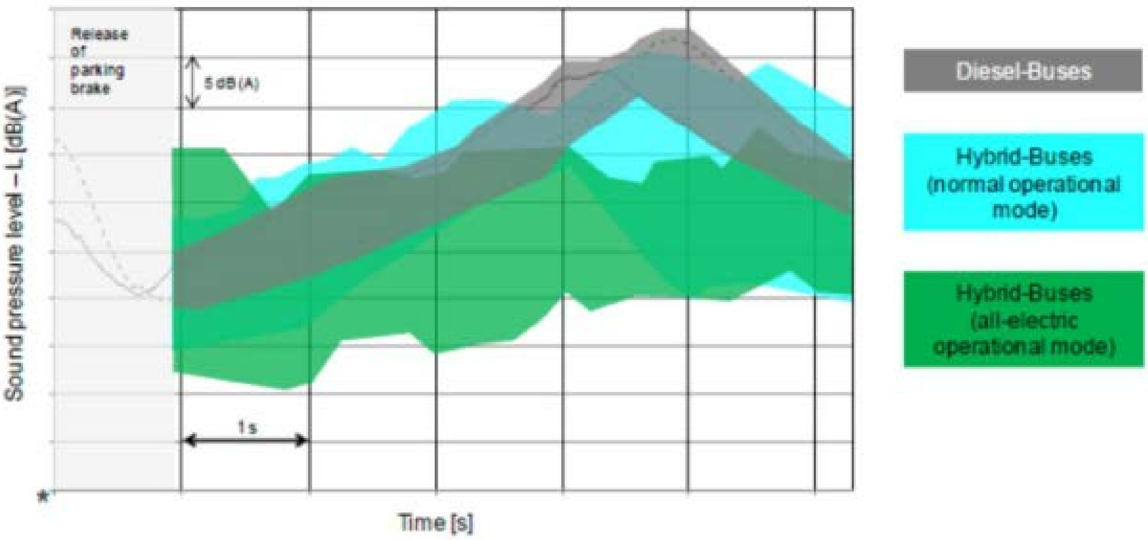
ICE vehicles provide limited scope for reducing sound levels at the source, and noise-reduction interventions for petrol or diesel buses are instead focused on reducing noise received by nearby populations – for example, by erecting noise barriers or installing quieter road surfaces (WHO, 2018). Upgraded road surfaces and/or noise barriers can be expensive to construct and may be required along many kilometres of traffic routes, which makes them unsuitable in many urban and suburban environments. Electric vehicles can help to reduce the reliance on treatments for the symptoms of noise pollution and can potentially be the cure for this issue. Laib (2019) concluded that at 20 km/h, one conventional ICE bus was as noisy as 25 all-electric buses.

City planners aim to make public transport as accessible as possible, and bus routes commonly pass through residential areas with bus stops located near to dwellings. In New Zealand specifically, the number of people living close to bus routes will increase as transit-oriented development becomes more common under the National Policy Statement for Urban Development, which encourages high-density development within rapid public transit walking catchments (New Zealand Government, 2020).

Living close to bus routes can be advantageous for travel purposes, but can lead to annoyance if noise, or other impacts, are not well managed. In Wellington, New Zealand, electric trolley buses were removed from service in 2017 due to infrastructure limitations and replaced with diesel buses. Local residents living along routes with a high number of buses soon complained about the higher level of noise from the diesel buses compared to the electric trolley buses they had become accustomed to, and one resident resorted to soundproofing his house in order to reduce sleep disturbance (Woolf, 2018).

Figure 2.2 shows that all-electric buses are upwards of 5 dBA[2] quieter than ICE buses when pulling away from bus stops (Biermann & Ruschmeyer, 2012). The median noise difference is up to 11 dBA within seconds of leaving a bus stop.

Figure 2.2 **Time history of sound pressure levels of diesel and hybrid buses leaving a bus stop.**



Source: Reprinted from Biermann & Ruschmeyer, 2012.

Laib (2019) demonstrated that traffic corridors with a high proportion of buses and a low average speed could benefit from the introduction of all-electric buses. On a quiet residential street, the overall noise reduction could reach 5 dBA (Laib, 2019), as shown in Figure 2.3. Interestingly, a 2014 study into noise radiation from a hybrid electric truck found that the greatest noise reduction benefits were gained in an upwards direction, implying that inhabitants of upper storeys would gain greater benefit from the lower noise emissions of electric vehicles than residents in lower storeys (Pallas, 2014b).

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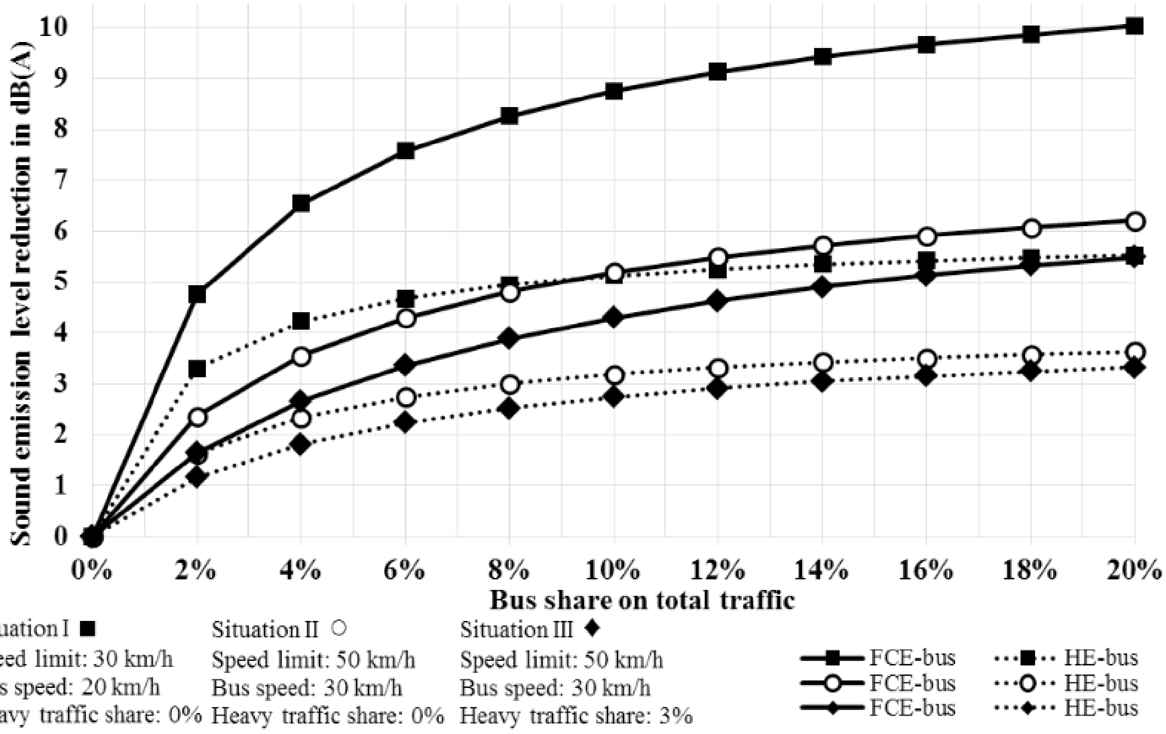
[2] ‘dBA’ refers to a decibel level that has its frequency characteristics modified by a filter (A-weighted) to approximate the frequency bias of the human ear.

Figure 2.3 Sound emission level reduction when replacing ICE buses with the studied electric buses as a function of the bus share of total traffic. Calculation for three situations using the hybrid electric (HE) or fuel cell electric (FCE) buses at bus stops.



Source: Reprinted from Laib, 2019, p. 383.

A reduction in traffic noise as a result of vehicle electrification could have societal advantages beyond health benefits. Financial benefits for a reduction in traffic noise pollution include lower health-related costs and a decrease in expenditure on noise reduction mitigation (Boren, 2020; Turcsany, 2016).

2.3 The disbenefits of quiet buses: Pedestrian safety

Clearly, electric vehicles can provide beneficial impacts on inner-city noise pollution, but they also generate new challenges, most notably in relation to road user safety. Electric or low-noise vehicles are calculated to be up to twice as likely to be involved in low-speed accidents with pedestrians or bicyclists as their ICE equivalents (Wu, 2011). Most buses currently used in Aotearoa New Zealand have loud diesel ICEs, which means pedestrians are accustomed to relying on a combination of visual and audio cues for detecting buses. The relative quiet of electric buses creates potential hazards to pedestrians who might not notice an approaching bus, which is a key risk when pedestrians and buses share the same road space. The risk is even greater for blind, low-vision, Deaf and low-hearing people, who are disproportionately affected by quiet buses, which are more difficult to detect.

Most literature related to pedestrian safety around electric vehicles focuses on the risks associated with electric cars or generalises the safety impacts of all electric vehicles. Here we note two studies that specifically mention the safety impacts of quiet electric buses on pedestrians.

Research into electric buses in Russia identified that pedestrians and cyclists are likely to fail to notice electric buses, increasing the probability of a collision or near miss (Gabsalikhova et al., 2018). A small part of this research involved interviews with the drivers of electric buses. All drivers reported feeling that they needed to be more cautious when driving the quieter electric buses as they were worried pedestrians would not notice the bus approaching and could step onto the road unexpectedly. The proposed solution to this problem was a pedestrian and cyclist recognition system fitted to the bus that would be able to detect other road users and automatically ‘honk’ to alert them to the presence of the bus (Gabsalikhova et al., 2018).

Similar research in Sweden, which involved interviews with truck and bus drivers, resulted in different findings to those of the Russian study (Shirnazard & Rõngelep, 2020). The drivers in the Swedish study tended not to perceive differences in the collision risks of electric heavy vehicles, compared to other heavy vehicles. The drivers reported that pedestrians and cyclists generally did not appear to be aware of the heavy vehicles around them, regardless of the engine type. Drivers blamed pedestrians and cyclists being distracted or using headphones as the main reason for their lack of attention (Shirnazard & Rõngelep, 2020). There is an increasing body of literature related to pedestrians being distracted. For example, a questionnaire study conducted in Japan found that 60% of participants admitted to wearing headphones while walking near trafficked areas (Yamauchi, 2017).

Evidence suggests that electric vehicles (all vehicle types – not only, or specifically, buses) are much more likely to be involved in crashes than ICE vehicles. Crash data published in 2009 in the United States showed that at low speeds, hybrid electric vehicles were twice as likely to be in a pedestrian crash than ICE vehicles (Hanna, 2009). Updated data using the same metrics in 2011 found this disparity had decreased, although hybrid electric vehicles were still 35% more likely to be involved in a pedestrian crash than ICE vehicles (Wu et al., 2011).

The ‘danger zone’ for accidents occurs when vehicles are travelling below 35 km/h. At these speeds, electric vehicles can be very quiet but are travelling at speeds that can cause death or serious injury. Swedish research found that at 30 km/h a car–pedestrian collision has a fatality rate of 2.7% and a severe injury rate of 14.7% (Kröyer, 2015). Collisions between pedestrians and buses are likely to incur higher levels of fatalities and injuries than this due to the weight, size and shape of the vehicles (Park et al., 2019). The risk of death or serious injury is even higher for young children and older adults (Kröyer, 2015).

The average speed for an urban bus in Auckland is 24 km/h,[3] which means many urban buses spend a lot of time in this danger zone. The average bus speed is low due to buses spending time waiting at stops and in traffic, as well as accelerating and decelerating into and out of stops. These manoeuvres occur at places where pedestrians are likely to be close to the road corridor or within the road corridor itself, which increases the risk of collision (Park et al., 2019).

Blind and low-vision pedestrians are at increased risk of collision with quiet electric vehicles because they rely heavily on audio cues for detecting the presence of a vehicle and on traffic noise for orientation (Liu et al., 2018; Vision Australia, 2019). Research in Australia provided detailed information about the experiences of blind and low-vision people and their perceptions of quiet electric vehicles (Liu et al., 2018). A survey of 246 blind and low-vision people found that 35% of survey participants had had a collision or near miss with an electric vehicle. Most of these collisions or near misses occurred when the survey participant was crossing the road, as shown in Figure 2.4.

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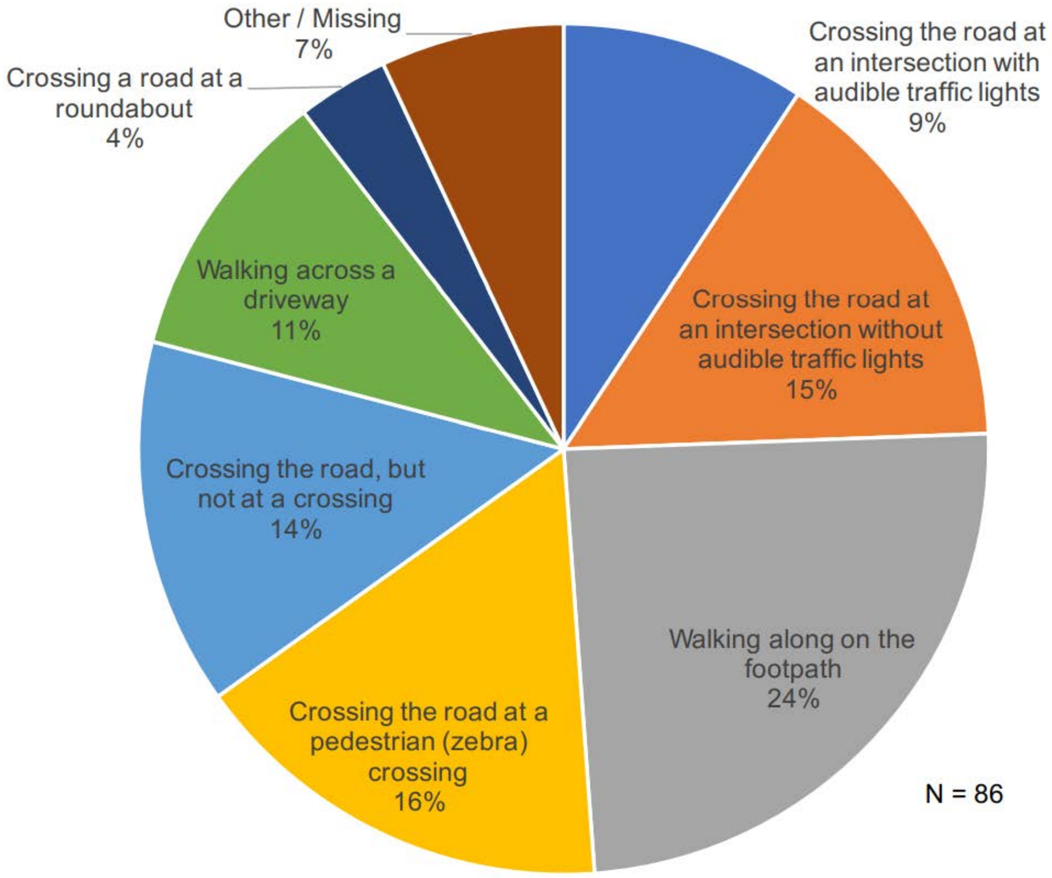
[3] S. Wrenn, personal communication, 1 November 2021.

Figure 2.4 Location of collisions or near misses between blind or low-vision pedestrians and hybrid or electric vehicles.



Source: Reprinted from Liu et al., 2018, p. 41.

Even if blind or low-vision pedestrians have not been involved in a collision or near miss, the presence of quiet electric vehicles may still affect their confidence and willingness to walk and cross roads. Of the survey participants reported above, only 26% reported that their confidence to walk and cross roads had not been affected (Liu et al., 2018). The rest of the participants reported feeling less confident, with 16% being affected in a large way. Importantly, 34% of survey participants reported that a collision or near miss had reduced the number of times they go out (Liu et al., 2018).

2.4 Interventions to reduce collision risk

Most of the interventions identified in the literature to overcome safety problems related to quiet electric vehicles involve the installation of an AVAS. Additional safety interventions that assist the driver of an electric vehicle in avoiding a collision are also identified. Safety interventions that give blind, low-vision, Deaf and low-hearing pedestrians tools to support their detection of electric vehicles are also suggested.

To date, it appears no published research is available that evaluates the use of AVASs in buses. We draw on a study that models the role of AVAS use on trucks in improving pedestrian safety. The Volvo Safety Report identifies collisions when heavy vehicles take-off from a standstill as a key cause of fatalities in urban areas (Shirnazard & Rõngelep, 2020). There is potential for this to worsen as heavy vehicles transition to electric powertrains and have quieter engines. In response, Volvo developed and tested an AVAS that included a take-off sound to alert surrounding road users when a heavy vehicle was about to move. This testing coincided with the European COVID-19 outbreak, so the testing was carried out in a digital environment (Shirnazard & Rõngelep, 2020). The study showed that research participants thought that the AVAS with a take-off sound improved safety as it was easier for them to notice the heavy vehicle when the sound was generated (Shirnazard & Rõngelep, 2020).

Beyond AVASs on buses themselves, a systematic approach to pedestrian safety may include, for example, high quality road crossings, with vehicle speeds managed through raised tables and good lighting. It may also include automatic braking systems on buses to reduce collision risk. We did not find any literature related to street infrastructure or automatic braking solutions that reduce collision risk.

2.4.1 UNECE Regulation No. 138: Promoting road user safety with AVASs

United Nations Economic Commission for Europe (UNECE) Regulation No. 138 was created in response to safety concerns with electric vehicles (United Nations, 2017). The UN recognises a heightened crash risk between quiet, slow-moving electric vehicles and pedestrians. UNECE Regulation No. 138 came into force for all Contracting Party countries on 1 July 2021. The regulation requires all quiet electric vehicles to meet a minimum noise level of 56 dBA when travelling below 20 km/h. Vehicles that do not meet this minimum noise level must have an approved AVAS installed to support detection of these otherwise silent vehicles by pedestrians.

AVASs increase the audibility and consequent detectability of approaching quiet vehicles, increasing safety for pedestrians, particularly vision-impaired pedestrians, cyclists, and other motorists (Hsieh, 2021). A Japanese study found that 85% of vision-impaired pedestrians felt threatened by vehicles that approached with low noise levels (Sakamoto, 2011), emphasising the need for development in this area.

Individual countries have been assessing the most appropriate AVAS solution for their needs. A warning system must be:

- loud enough that it is not masked by ambient noise
- identifiable as a moving vehicle
- unintrusive so as not to cause disturbance or annoyance (Lee, 2017).

The Japanese government has prohibited the use of tonal alerting systems because these are likely to cause annoyance (Poveda-Martínez et al., 2017).

2.4.2 Different AVAS options

In the UK, in response to UNECE Regulation No. 138, Transport for London (2019) has been collaborating with Guide Dogs for the Blind and other accessibility groups to trial alerting systems on electric buses across the capital city. Transport for London developed and trialled a unique AVAS on electric buses in the Tottenham area. When the bus is stationary, speakers at its front play an F# major chord. This is supplemented by a C# pulsing tone when the bus is in motion (D&AD Awards, 2020). When the bus is travelling faster than 20 km/h the sound cuts out, as the road noise is loud enough for the bus to be heard (Shirnazard & Rõngelep, 2020). While the results of this trial are not publicly available, it is hoped that the AVAS will improve the detectability of Tottenham’s electric buses and reduce the likelihood of pedestrian–bus collisions and near misses (Shirnazard & Rõngelep, 2020). This trial is likely to inform AVASs across the wider public transport network of London by ensuring that detection systems for electric buses are credible and recognisable.

Practical trials, with collaboration with the most affected parties, are a valuable aspect of AVAS development. While AVASs have the potential to increase the safety of road users, compared to a situation where electric vehicles do not produce warning sounds, it is important that vulnerable road users are aware of what to expect from electric vehicles. A questionnaire survey conducted in Japan found that while 67% of participants deemed AVASs to be necessary, over half of the participants did not know what sound to expect from such a warning system (Yamauchi, 2017).

Urban soundscapes vary widely in noise level, contributing elements and spectral content (Poveda-Martínez et al., 2017). An effective AVAS must be detectable within a range of ambient environments from quiet suburbs to heavily industrialised areas and busy city centres. A 2021 study investigating the detectability of AVAS-type sound in different ambient environments recorded at a busy eight-lane traffic intersection in China found that high frequency sounds required a sound pressure level of 84–86 dBA in order to be heard in all ambient settings, while medium and low frequency sounds needed to exceed 100 dBA in order to be detected in all test scenarios (Hsieh, 2021). Such high sound levels are unfeasible for everyday AVAS equipment in sub-urban, or quieter urban, areas, but highlight the considerations that must be made when designing a suitable alerting sound. It should be noted that some traditional ICE vehicles would likely have failed detection in the tested ambient scenarios (Hsieh, 2021).

Other solutions for collision risk mentioned in the literature include:

- the use of vehicle detection systems to warn people at pedestrian crossings (Verheijen & Jabben, 2010)
- automatic braking systems and collision evasion systems (Liu et al., 2018; Misdariis & Pardo, 2017)
- collision warning systems (Liu et al., 2018)
- recognition of electric vehicles in guide dog training (Sandberg, 2012)
- mobile apps that can alert blind, low-vision, Deaf and low-hearing pedestrians to the presence of an electric vehicle (Liu et al., 2018).

Some researchers suggest that these solutions are considered as *additional* safety interventions rather than alternatives to AVASs due to the recognised safety improvements AVASs create for blind and low-vision pedestrians. It is also vital that blind and low-vision pedestrians *know* they will be able to detect an electric vehicle through AVASs – without this knowledge they risk losing their confidence to walk and cross roads (Liu et al., 2018). Using a combination of safety interventions makes it more likely that most people will be able to detect an electric vehicle in some way, keeping in mind that Deaf and low-hearing pedestrians are less likely to benefit from AVASs (Liu et al., 2018).

2.5 The disbenefits of quiet buses: Accessibility – detecting and hailing a bus

While collision avoidance is one reason for quiet buses to increase their detectability, another reason is that members of the community must be able to detect buses in order to board them and travel on them. Much of the literature about the accessibility of buses to blind, low-vision, Deaf and low-hearing passengers focuses on locating bus stops and accessing visual and audio information while travelling on a bus. No published literature was found that focused specifically on the inaccessibility of detecting and hailing buses.

In its submission on the New South Wales Government’s inquiry into electric buses, Vision Australia (2019) identifies buses as the least accessible mode of public transport for blind or low-vision people, a sentiment supported by the Association of Blind Citizens of New Zealand Inc (n.d.). This is because identifying and hailing a bus relies heavily on being able to see buses as they approach the stop. Blind and low-vision passengers must rely on the sound of vehicles approaching, and it can be difficult to differentiate between buses and other heavy vehicles (Association of Blind Citizens of New Zealand Inc, n.d.). The introduction of quiet electric buses will worsen this problem, as it will become more difficult to hear the noise of the bus approaching (Vision Australia, 2019).

In Aotearoa New Zealand, many public transport providers have policies requiring bus drivers to stop at a bus stop when they see someone with a white cane or guide dog, even when they are not actively hailing the bus (Metro Christchurch, n.d.). Despite this, there are multiple reported cases around the country of blind and low-vision people being left at bus stops by drivers (Campbell & Thomas, 2015; James, 2020; Preston, 2012; RNZ, 2020).

2.6 Interventions to improve bus detection by passengers

Very little peer-reviewed literature explores interventions to improve the detection of buses by blind and low-vision passengers. No literature is available about detection of buses by Deaf and low-hearing passengers. Most of the published literature focuses on the creation of technologies that are not publicly available, or that have not been tested by blind and low-vision people. This section discusses those technologies.

2.6.1 Transit App

The Transit App is already available throughout Aotearoa New Zealand, in Auckland, Hamilton, Christchurch, Tauranga, Timaru and Wellington. The app provides real-time tracking with updates on how far away the user's bus is. A useful aspect of the app is the 'alert' feature, which can tell the user when the bus is one minute away so they can prepare to board the bus (Transit, 2019).

Information is presented visually but is compatible with Android and iOS screen readers. This means blind and low-vision users can receive spoken information for when their bus is pulling up to their stop (Transit, 2019).

One limitation of the Transit App is that it does not overcome the problems that occur when multiple buses are pulling into the stop at once. This is a common occurrence at rapid transit stops and inner-city streets that host multiple bus routes. Therefore, a blind or low-vision passenger still has to rely on the kindness of other passengers or the drivers to determine which bus to board. An additional limitation is the requirement for a smartphone connected to Wi-Fi or mobile data in order to operate the app. This excludes people without a smartphone, or without the funds to pay for mobile data.

2.6.2 Real-time information boards

Some popular bus stops in Aotearoa's larger cities have real-time information available on an electronic message board, supported by audio information (Busit, n.d.; Printed Electronics World, 2019). Deaf and low-hearing passengers can view the real-time information on the message board, while blind and low-vision passengers can press a button to have real-time information presented in an audio format.

Unlike smartphone apps, presenting real time data at bus stops has a democratising effect because it does not require access to a smartphone or data connection. Yet, there are reports of electronic message boards being unreliable and resulting in people being stranded at bus stops (Orsman, 2021; Te, 2017). Moreover, this type of intervention does not solve the problem of identifying which bus is the correct one to board when there are multiple buses at a stop, and these are not usually available in less dense suburban locations.

2.6.3 Talking buses

Some international cities have a 'talking bus' feature, which announces the bus route name and destination to passengers waiting at a stop, as the bus pulls up. An example of this type of intervention exists in

Honolulu, Hawaiʻi. An automated announcement with the current stop, route number and destination is generated when the bus pulls into a stop (Keany, 2011).

This type of intervention is beneficial as it does not rely on individual passengers having access to a smart phone or data connection. It also reduces challenges in identifying which bus a person wants to board when there are multiple buses at a stop.

2.7 Research gaps

We did not find any literature on the effects of quiet electric buses on Deaf and low-hearing people, or any mention of disabled people in the studies we cited. It is possible that the switch to quiet electric buses from louder ICE buses may mean the noise of approaching buses is below the threshold that some low-hearing people can detect. It is also possible that the change in noise level may not affect Deaf and low-hearing people’s ability to detect an approaching bus if they already rely solely on visual cues.

Neither did we find any literature on the specific impacts of bus AVAS use on pedestrian safety. There are no published evaluations of the effectiveness of AVASs on either pedestrian perceptions of safety or on reported crashes. Additionally, we did not find any detailed literature about the annoyance factor of AVASs outside of one report that highlighted the potential for tonal AVASs to be annoying to pedestrians (Poveda-Martínez, et al., 2017).

3 Research methods and results

The research methods involved two components.

1. **Control testing** involved measuring the noise of electric and diesel buses in quiet, controlled conditions with as little ambient noise as possible.
2. **Participant testing** involved volunteers spending time on a path next to a bus route and alerting researchers when they heard an approaching bus.

Each method and its results are presented here.

3.1 Control testing

3.1.1 Purpose

Controlled on-street bus noise surveys were undertaken in Auckland to obtain clean measurements of electric and diesel bus passes at pre-determined speeds. The data recorded during the surveys was intended to provide baseline comparison information regarding the sound levels produced by different types of buses, and for potential future use in sound laboratory facilities.

3.1.2 Procedure

On 20 December 2021, we undertook noise measurements of controlled bus passes. Auckland Transport provided an electric bus and a diesel bus (Figure 3.1), each with a driver. Auckland Transport personnel also suggested the location of the testing and assisted with briefing the bus drivers.

The survey was undertaken on the corner of Cornerstone Drive and Spray Rise, Albany. This area is currently largely undeveloped. A construction site was active nearby at 6-8 Munroe Lane, which had some limited effects on the survey results (Figure 3.2).

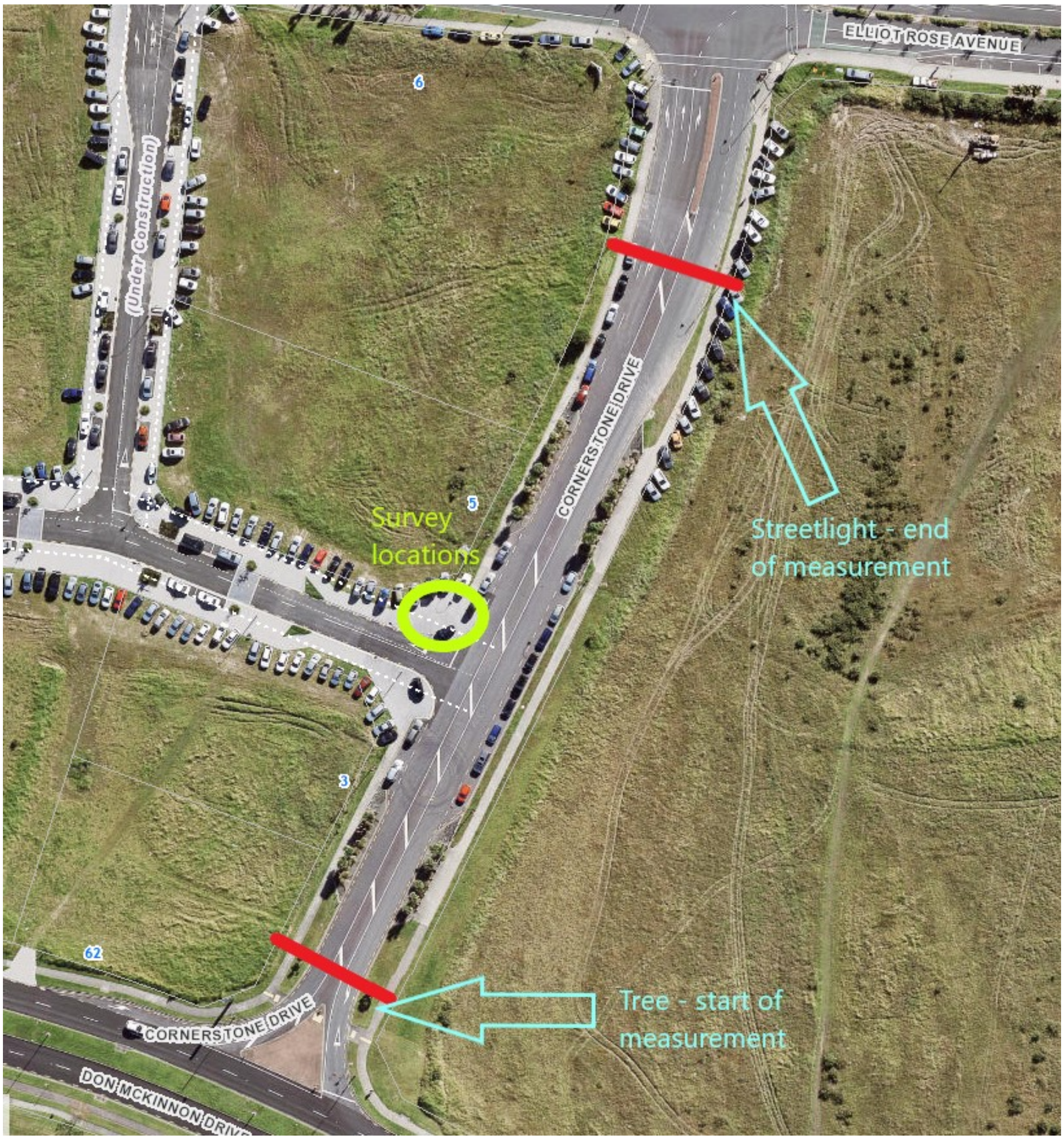
Figure 3.1 Electric bus (left), diesel bus (right)

The buses completed a looping route, passing the survey setup on Cornerstone Drive in the closest traffic lane. Buses travelled north on Cornerstone Drive, then turned left into Elliot Rose Avenue, Munroe Lane and Don McKinnon Drive before passing the survey location again. The road surface of Cornerstone Drive adjacent to the survey position is new, smooth asphaltic concrete (AC-10), which is considered a low-noise road surface. Therefore, tyre noise would be reduced as far as practicable.

For each bus, we measured three passes at three different constant speeds: 10, 30, and 50 km/h. Bus drivers were instructed to pass the survey position at a steady speed. In total, nine valid measurements per bus were analysed (ie, three passes at each speed).

The measurement parameters during the trial were L_{Aeq} and L_{AFmax}.[4] The survey duration for each pass was determined by buses passing a specific tree on approach (approximately 77 m from the survey positions) and a streetlight after passing (approximately 85 m from the survey positions). The survey extent is shown in Figure 3.2. Each survey extent varied, depending on the speed of the passing bus: 10 to 12 seconds for pass bys at 50 km/h, 15 to 17 seconds for pass bys at 30 km/h, and 40 to 43 seconds for pass bys at 10 km/h.

Figure 3.2 Survey extent



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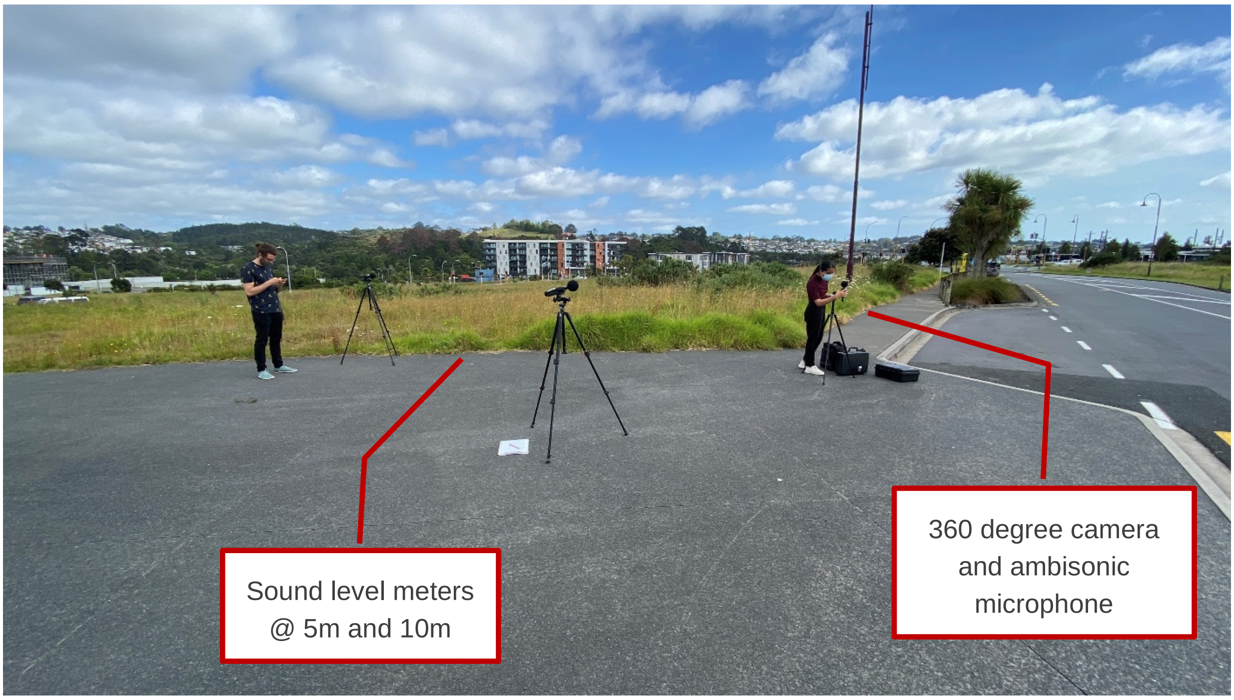
[4] 'L_{AFmax}' is the A-weighted maximum noise level with fast time weighting. It is the highest noise level that occurs during the measurement period.

Measurements that did not provide a clean result were discarded and repeated. This was the case when other buses were passing the survey location at the same time as the test bus, when construction had an obvious influence on the measured levels or when the test bus did not pass the location at a steady speed (eg, if the bus braked too soon after passing the location). Where the effects of such interference were minimal, the result was still included in the assessment, but marked accordingly.

The survey setup included two sound level meters set at 5 m and 10 m from the kerb for noise level measurements. In addition, we set up a 360-degree camera and an ambisonic microphone closer to the kerb to obtain video and audio recording of the bus passes.

A layout of our setup is shown below in Figure 3.3.

Figure 3.3 Controlled test setup



We measured ambient sound levels without bus or car passes prior to the bus passes. Ambient sound levels were determined by distant traffic and construction noise and wind in trees. The levels were 58 dB L_{Aeq} and 47 dB L_{A90}.[5]

3.1.3 Results

A summary of our survey results is shown in Table 3.1.

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[5] 'L_{A90}' is the A-weighted noise level equalled or exceeded for 90% of the measurement period. This is commonly referred to as the background noise level.

Table 3.1 Survey result summary – Mean of the three passes per bus type and speed

Speed (km/h)	Bus type	Energy average dB $L_{Aeq(T)}$*	
		@ 5 m	@ 10 m
10	Electric	55	51
	Diesel	63	58
30	Electric	62	58
	Diesel	63	59
50	Electric	69	65
	Diesel	66	62

* (T) was dependent on the passing speed, as discussed above Figure 3.2.

In summary, the electric bus in this study was found to be:

- significantly quieter (7 to 8 dB) than the diesel bus at very low speed (10 km/h)
- similar in sound level (±1 dB) at slow speed (30 km/h)
- potentially noisier (3 dB louder) than the diesel bus at higher speeds (50 km/h).

We suspect that the tyre types fitted to the two buses might have differed, resulting in a louder tyre/road interaction noise for the electric bus at 50 km/h, and we note that the electric bus had six wheels rather than the diesel bus's four, which, all things being equal, would add 1–2 dB to the noise levels. Per the literature review (refer Figure 2.1), we note that above 40 km/h, the only major noise source produced by electric buses is tyre noise.

We clearly noticed that the tyre noise was dominant at 50 km/h. At lower speeds, tyre noise was nearly inaudible over the engine noise of the diesel bus and the condenser noise of the electric bus.

3.2 Participant testing

3.2.1 Purpose

To investigate the detectability of electric and diesel buses in a real-world situation, we conducted on-street trials in Wellington and Auckland in February 2022. Electric buses are currently consistently utilised on two bus routes in Wellington and one route in Auckland. These cities were chosen because of the frequency of both diesel and electric buses, making it possible to run trials with participants attending for two hours at a time.

The participant testing was exploratory rather than formally experimental. We were interested to measure the sound levels of buses and ambient environments in real-world contexts, exploring any clear differences between detection of diesel and electric buses, rather than testing all possible noise scenarios. As the locations were on public streets that were not closed for testing, it was not possible to control all variables affecting sound.

3.2.2 Participants

We recruited volunteer participants from the community for the detection trials. Participants were recruited through personal contacts and through the disability communities in Auckland and Wellington. We recruited participants with low or no vision, as well as non-disabled participants. People with little or no vision are known to use their sense of hearing differently from other people, so we wanted to test detectability for both groups.

Participants comprised eight people with little or no vision (five in Wellington and three in Auckland) and seven non-disabled people (two in Wellington and five in Auckland). Two of the low-vision participants also reported impaired hearing, one of whom used hearing aids that adjusted their hearing to normal. Different participants were recruited for the Wellington and Auckland trials – that is, there were 15 distinct volunteer participants taking part in this trial.

3.2.3 Procedure

During each test session, two participants sat on the footpath along a test bus route next to a microphone that was recording ambient noise and the sound of passing buses. Due to the ongoing COVID-19 public health situation, adequate social distancing was maintained between participants. The participants were seated facing away from the direction of bus approach (to minimise visual detection) and were asked to raise a hand when they audibly detected an approaching bus. Both electric and diesel buses were detected using the same method.

Traffic cones or sandbags were laid out along the road to mark 10-metre increments so the distance at which buses were detected could be noted. Distances were noted as ‘positive’ distances when detected prior to reaching the participants, and as ‘negative’ distances when the bus was detected only after passing the participants. While bus detections at ‘negative’ distances (ie, when they had passed the participants) have been recorded, we acknowledge that non-disabled participants may have used visual clues to detect a passing bus. We discuss this further in the results section of the report.

Marshall Day Acoustics and MRCagney personnel on site made detailed notes, and a camera was set up to record the trials to allow the project researchers to review the findings. In Wellington, participants were warned to expect a bus when a project researcher sighted that a bus was approaching along the road (approximately one to two minutes before its arrival). This was not required in Auckland because buses passed much more frequently at the survey location.

In addition to the target buses, participants were also asked to raise their hand for other noise sources that sounded like a bus to give an indication of the audible characteristics of buses.

3.2.4 Locations

3.2.4.1 Wellington

Wellington trials happened on 1 and 2 February 2022. The study location was on the west side of Adelaide Road, by Wakefield Park, Island Bay, along bus route 1, which is serviced by both diesel and electric buses. Participants were located on the grass berm alongside the footpath, under trees (Figure 3.4). The location was approximately halfway between bus-stop ‘The Parade (near 36)’ and bus-stop ‘Adelaide Road at Duppa Street’, Island Bay, meaning that buses passed the study location at speed and did not stop. The target buses for identification were driving northbound, on their way into Wellington city. The buses passed the testing location on an uphill incline where the speed limit is 50 km/h and the road surface is AC-15.

Each volunteer was asked to detect a total of 10 target buses, meaning that each session lasted approximately 1.5 to 2 hours. During the first of three sessions on 2 February, the two participants were asked to detect 9 buses, instead of 10, due to windy conditions (discussed in section 3.2.5).

Figure 3.4 **On-street testing set-up, Wellington**

3.2.4.2 Auckland

In Auckland, on-street trials were conducted on 22 February 2022 on Queen Street in the central business district. The study location was on the west side of Queen Street, just north of Q Theatre. Queen Street is serviced by both diesel and electric buses. Queen Street is relatively flat in this location. The speed limit is 30 km/h, and the road surface material is AC-14.

Participants were located on the footpath facing north. The survey location was 30 m north of a bus stop and 50 m north of a traffic-signal-controlled intersection (both of which are shown in Figure 3.5). Another (temporary) bus stop was situated 30 m north of the location (ie, the survey location was 30 m from either stop). Some buses passed the study location at speed, while others were accelerating from the bus stop to the south or decelerating to the bus stop to the north. For the purposes of this study, only detections of buses that passed by at speed and on the same side of the road as the participants were included. Buses that were accelerating away from or decelerating towards bus stops were not included as data points to maintain consistency with the Wellington data and to reduce a variable of the study. Bus passes that did not fulfil the target bus requirements were excluded at the discretion of the staff onsite.

Each volunteer was asked to detect a total of at least 10 target buses, stopping when at least three electric buses had passed by. Each session lasted one to two hours.

Figure 3.5 On-street testing set-up, Auckland

3.2.5 Results

In total, as set out in section 3.2.2 above, the on-street tests featured eight low/no vision participants and seven non-impaired participants. Based on the poor performance of the hearing-impaired participant in the Wellington sample (discussed below), their detections were removed from the sample, resulting in a final sample size of seven low/no vision participants and seven non-impaired participants. A total of 186 data points were obtained from the resulting 14 participants across both cities.

A summary of the Wellington and Auckland on-street testing results is provided in Table 3.2.

Table 3.2 Summary of Wellington and Auckland results

	Wellington	Auckland
Ambient environment	Open, suburban environment	High-rise city centre location
Total number of target buses	58 (44 diesel, 14 electric)	128 (88 diesel, 40 electric)
Number of diesel buses	44 (41 detected, 2 detected once passed, 1 not detected)	88 (74 detected, 3 detected once passed, 11 not detected)
Number of electric buses	14 (7 detected, 5 detected once passed, 2 not detected)	40 (14 detected, 4 detected once passed, 22 not detected)
Detection distances	Diesel: > 50 m to −15 m Electric: 15 m to −15 m	Diesel: > 50 m to −10 m Electric: > 50 m to −5 m
Other noise sources	Wind noise, cicadas, other traffic	Other traffic, reflections off buildings

3.2.5.1 Wellington results

As stated, the on-street testing was conducted over two days in Wellington. The weather conditions were calm and sunny on 1 February, with winds of 7 km/h or less. On 2 February the weather conditions were overcast and humid, with wind conditions that were gustier (and therefore, noisier) than would have been desirable (around 20 km/h), but we persisted with the testing as we thought it was important to gather data in an authentic real-world scenario. On both days of testing, cicadas were present in the trees above the participants, and their sound is notable in the acoustic recordings (though cicadas generated sound at a different frequency to traffic).

Although the speed limit of the road was 50 km/h, the bus drivers had been notified of the on-street trials and most passed by at 20–30 km/h. Since we had no influence on the speed, we proceeded with the surveys irrespective of the unusually slow speed for this location.

As mentioned above, one of the Wellington participants was hearing impaired, as well as low vision. This participant had the opportunity to detect seven diesel buses and three electric buses. Only three of the diesel buses were detected (although all were level with, or had already passed, the participant before detection), and no other buses were detected. As this participant failed to detect the majority of buses, and their impairment would put them in a group of ‘one’ with no equivalent participants to compare with, we decided not to include their data points with the results from the other participants.

The remaining participants were exposed to a total of 58 bus passes (44 diesel bus passes and 14 electric bus passes). As shown in Figure 3.6, of these, one diesel bus pass was not detected at all, and two electric bus passes were not detected at all. The majority of diesel buses were detected between 0 and 15 m distance as the bus approached the participants. Diesel bus detection distances ranged from more than 50 m (for a particularly loud old diesel double decker bus) to between −10 and −15 m (after the bus had passed the participants). Of the diesel buses, 93% (41 of 44) were detected before they had passed the participants. Detection distances for electric buses ranged from 15 m to −15 m, prior to or after the bus had passed. Seven of the electric bus detections were made as the bus approached the participants, and five detections were made once the bus had passed by.

The data in Figure 3.6 were analysed with Chi-squared tests of independence. There was no significant difference in the two detection categories (early (beyond 5 m of the participant) and late (within 5 m or passed the participant)) by engine type (electric or diesel).

The difference in detection distance (for diesel and electric buses combined) between low-vision participants and non-impaired participants in Wellington is shown in Figure 3.7. These data were analysed with Chi-squared tests of independence. There was no significant difference in detection category by participant impairment type. Full results of statistical analyses are included in Appendix A.

Figure 3.6 Distances at which buses were detected by participants in Wellington

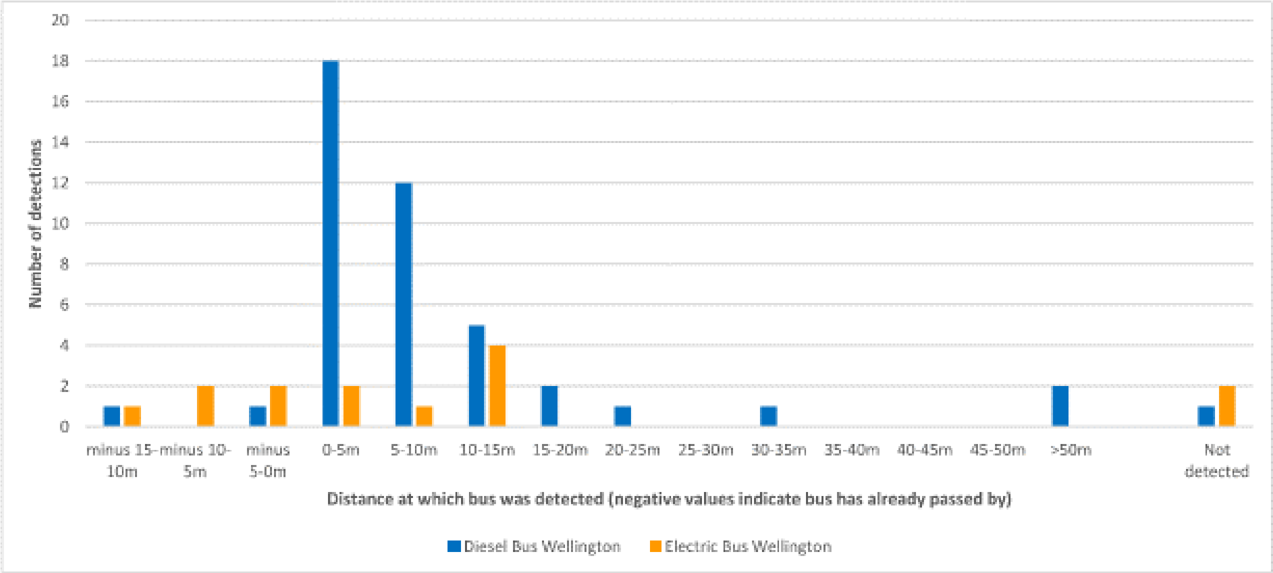
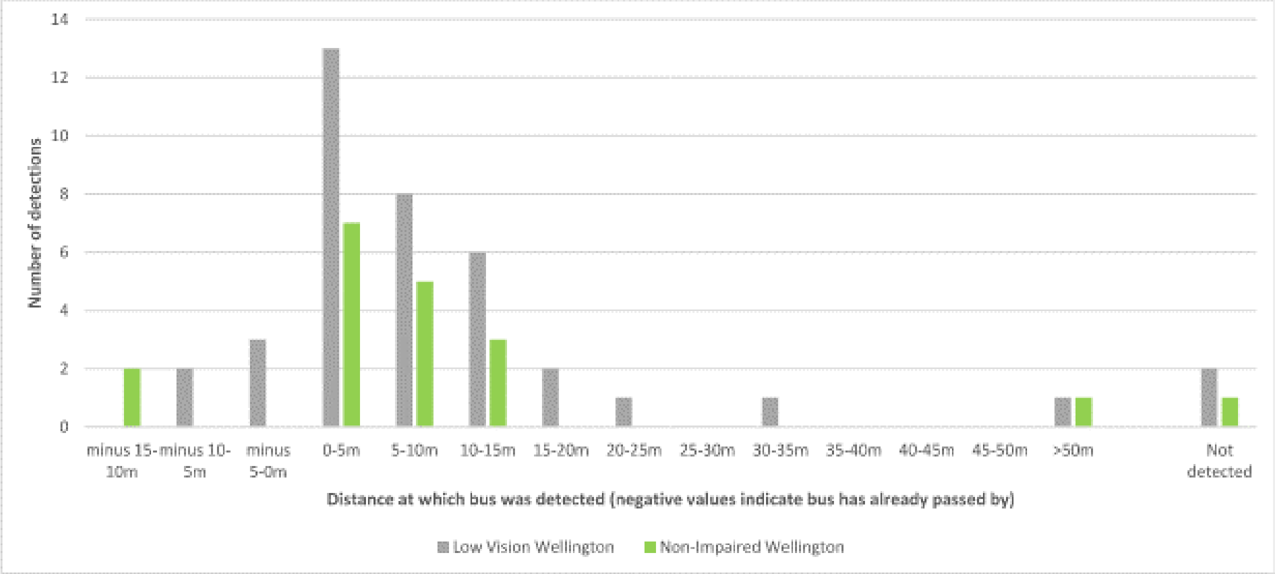


Figure 3.7 Detection distances for low-vision vs non-impaired participants in Wellington



3.2.5.2 Auckland results

As noted, on-street testing was conducted on 22 February in Auckland between 9 am and 5 pm. The weather conditions were calm and sunny, with between 0 and 3 oktas cloud cover, and winds of 10 km/h or less from east and north northeast. The ambient noise environment was representative of a busy urban area, and there seemed to be some sound reflection off the surrounding buildings, creating a semi-reverberant effect. Buses passed by at speeds between 10 and 30 km/h.

The traffic lights 50 m to the south sometimes influenced the participants' ability to detect diesel buses as their engine note changed when the traffic lights switched from red to green. A similar phenomenon was not present for electric buses. The distinctive sound of diesel bus engines at acceleration from standing, while relevant as noted in our test setup, has no significant bearing on the detectability of buses in the context of this study. The noted distinct diesel engine sound would occur at bus stops when buses leave (ie, the person would have missed the bus) and when buses start from a red light at an intersection (which hopefully will have audible signals for vision-impaired people to be aware of the phasing).

As mentioned, one of the Auckland low-vision participants was hearing impaired and used hearing aids. Because hearing aids are intended to correct hearing to normal, we have considered them in the same group as the rest of the low-vision participants. It should be noted, however, that this participant detected only 7 of 17 bus passes. The participant informed us that their hearing aids were directional, with greatest effectiveness for sound that occurred in front of them. As noted, we had asked participants to face away from the direction of approaching buses to minimise visual detection, and therefore the hearing aids were unlikely to be fully effective for this task. However, three of the seven detections made by this participant occurred when the bus was behind them (at 15, 25 and 35 m), so we decided to retain their data in the assessment.

The Auckland participants were exposed to a total of 128 bus passes (88 diesel bus passes and 40 electric bus passes). Figure 3.8 shows that 11 of the 88 diesel bus passes were not detected at all (12.5%), and 22 of the 40 electric bus passes were not detected at all (55%). Proportionally, and in absolute terms, more buses were undetected in Auckland than in Wellington.

Diesel bus detection distances ranged from more than 50 m to −10 m (after the bus had passed the participants). Of the detected diesel buses, 74 of 77 (96%) were detected before they had passed by. Electric buses were detected up to > 50 m away, but most were detected between 15 m and −5 m (Figure 3.8). Of the detected electric buses, 14 out of 18 (78%) were detected before they had passed by.

The data in Figure 3.8 were analysed with Chi-squared tests of independence. Diesel buses were significantly more likely to be detected early (beyond 5 m of the participant). Given the large number of non-detections in Auckland, we also tested the difference between detection (all distances) and non-detection for Auckland. Electric buses were significantly more likely to be missed (not detected) than diesel buses.

Data in Figure 3.9 show the difference in detection distance for all buses combined, separated by low-vision and non-impaired participants. These data were analysed with Chi-squared tests of independence. Low-vision participants in Auckland were significantly less likely to detect a bus early than non-impaired participants. However, they were no more or less likely to miss a bus completely. Full results of statistical analyses are included in Appendix A.

Figure 3.8 Distances at which buses were detected by participants in Auckland

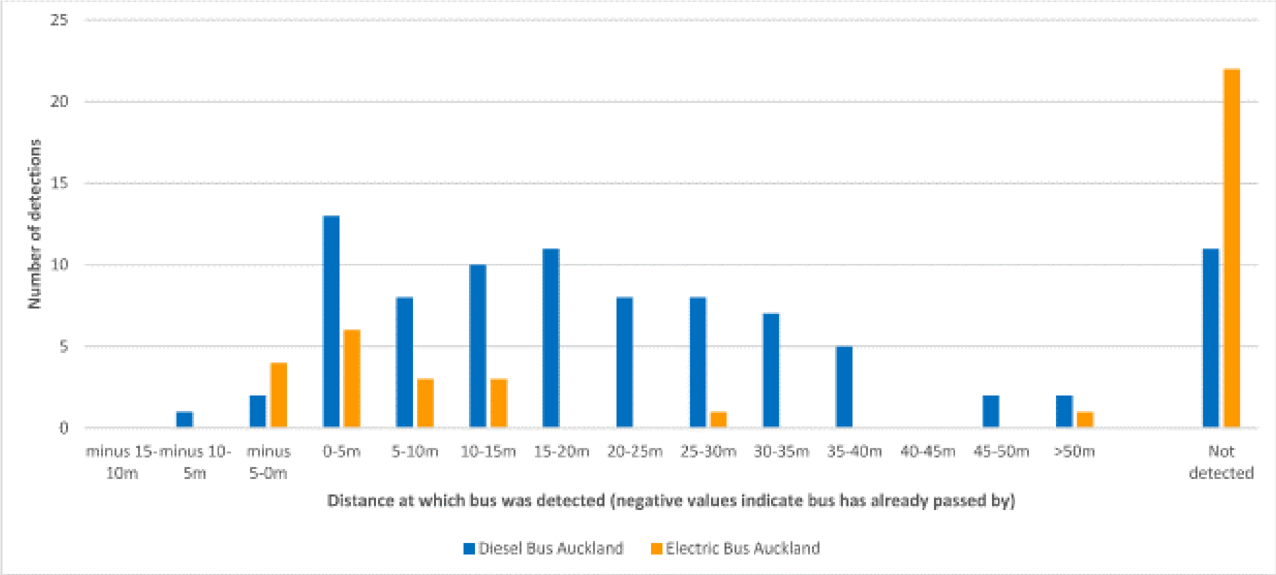
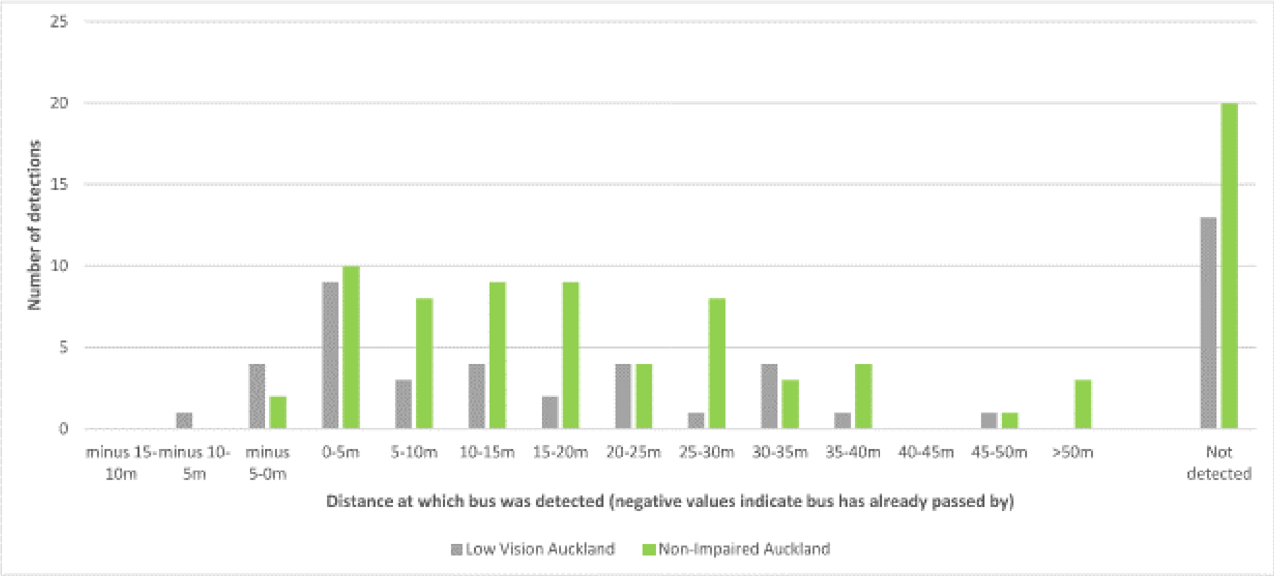


Figure 3.9 Detection distances for low-vision vs non-impaired participants in Auckland



3.2.5.3 Acoustic analysis

Ambient sound levels

One of our initial assumptions was that the sound level of a passing bus would need to be louder than the ambient noise level for the participants to detect and distinguish the bus.

The ambient sound levels ($L_{Aeq(T)}$) for each survey were as follows:

- Wellington day 1, survey 1: 65.2 dB $L_{Aeq(1h:30min)}$
- Wellington day 2, survey 1: 65.4 dB $L_{Aeq(1h:20min)}$
- Wellington day 2, survey 2: 64.7 dB $L_{Aeq(1h:15min)}$

- Wellington day 2, survey 3: 64.5 dB $L_{Aeq(1h:10min)}$
- Auckland survey 1: 65.9 dB $L_{Aeq(30min)}$
- Auckland survey 2: 65.6 dB $L_{Aeq(30min)}$
- Auckland survey 3: 65.6 dB $L_{Aeq(30min)}$
- Auckland survey 4: 66.0 dB $L_{Aeq(30min)}$

The average ambient sound levels were 65 dB L_{Aeq} for Wellington and 66 dB L_{Aeq} for Auckland.

The ambient noise levels measured at the Auckland survey location were on average 1 dB higher than the ambient noise levels measured in Wellington. Ambient noise levels varied by less than 2 dB across all surveys and both cities.

We have not reported the maximum noise levels for each survey (L_{AFmax}) as talking sometimes occurred close to the microphone outside of bus approach periods.

Detection noise level vs ambient sound level

We have analysed a subset of the bus detections to determine the sound level at the time the participants put up their hands to indicate a detection. The subset relates to the first person of each participant pair to put up their hand and does not include the second notification of the pair. The sound levels of Wellington detections are illustrated in Figure 3.10, and for Auckland in Figure 3.11.

Figure 3.10 A subset of sound levels at which Wellington participants put up their hands to indicate bus detection. The vertical red line provides an indication of the ambient sound level (65 dB L_{Aeq}).

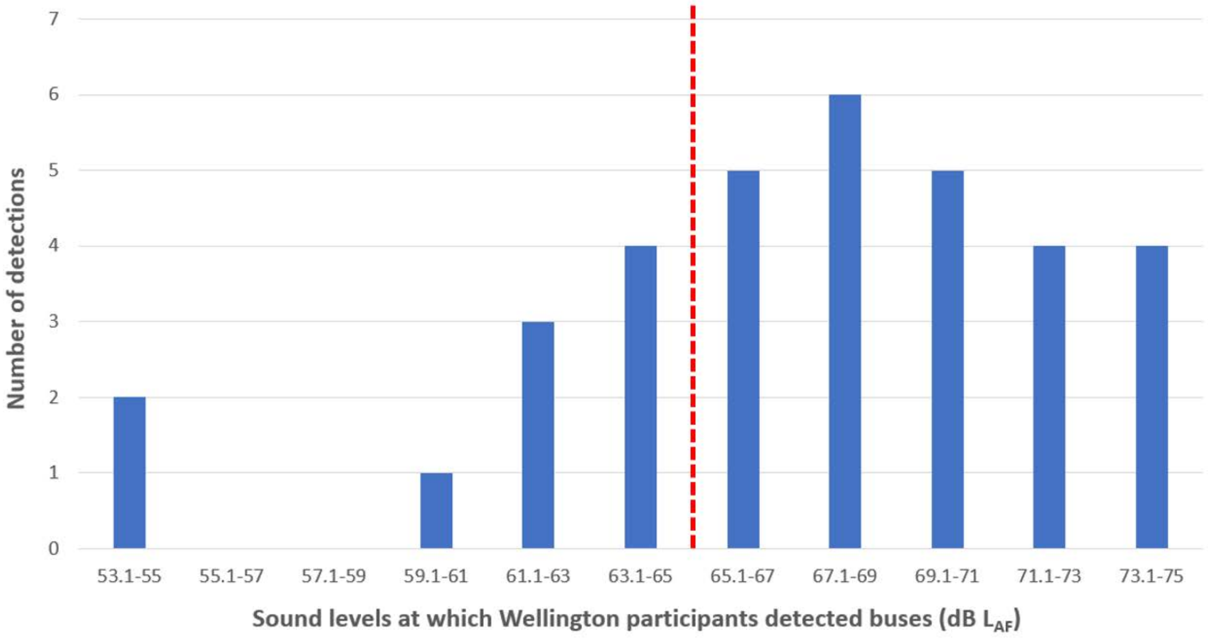
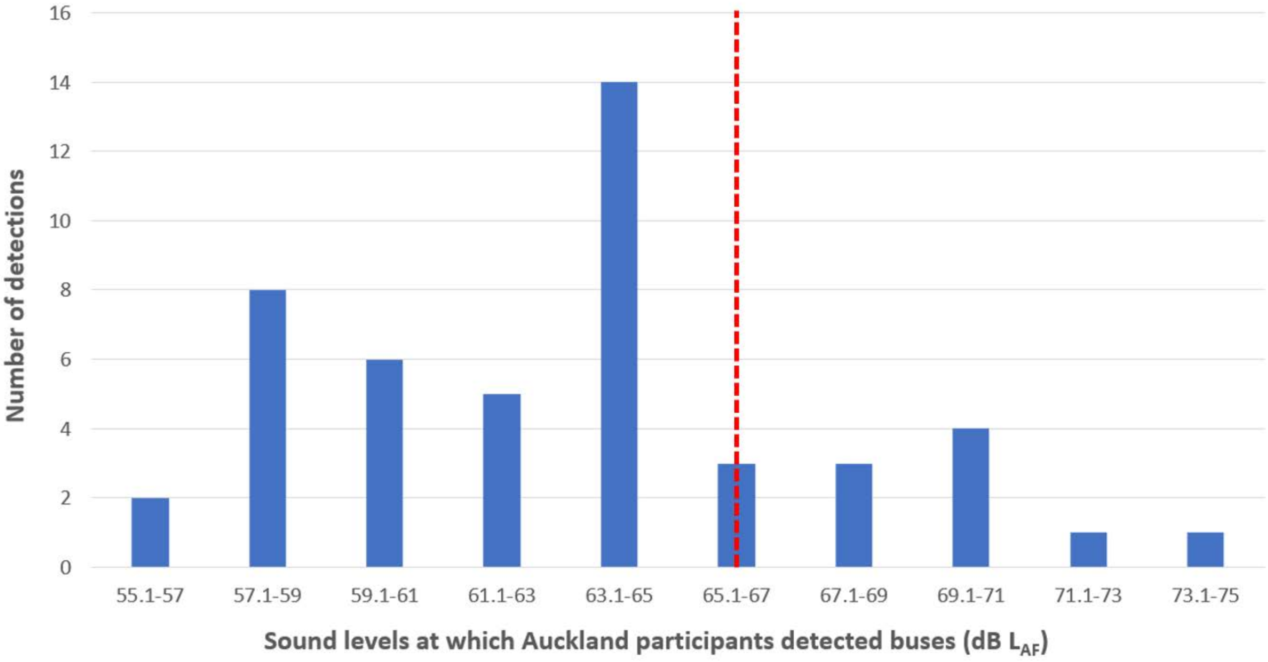


Figure 3.11 **A subset of sound levels at which Auckland participants put up their hands to indicate bus detection. The vertical red line provides an indication of the ambient sound level (68 dB L_{Aeq}).**



In Wellington, diesel buses were detected at sound levels from 53 to 75 dB L_{AF}, and electric buses were detected at sound levels from 60 to 70 dB L_{AF}.

In Auckland, diesel buses were detected at sound levels from 56 to 75 dB L_{AF}, and electric buses were detected at sound levels from 57 to 71 dB L_{AF}.

Our assumption was that buses would be most commonly detected when their sound level was louder than the ambient (background) noise level. Indeed, Figure 3.10 demonstrates that the majority of buses (both electric and diesel) were detected with sound levels that were higher than the ambient noise level in Wellington. However, on some occasions in Wellington and for the majority of bus detections in Auckland, we found that buses were detected at sound levels that were quieter than the ambient noise level (when you would expect that the sound couldn't be heard), which suggests that the detection of a bus is not related solely to the loudness of its sound (Figure 3.10 and Figure 3.11). Detectability also seemed to be related to the character of the sound – that is, the distinctiveness of the sound, which is defined by the frequency content of the sound.

Sound energy by frequency – Overall noise

We have compared the frequency content of the sound produced by electric and diesel buses. Figure 3.12 and Figure 3.13 show spectrograms of sound energy for the controlled 30 km/h bus passes recorded during the Auckland controlled tests. A spectrogram is a visualisation of the sound energy across time (*x* axis) and frequency (*y* axis) where colours represent the intensity of the sound. We have encircled the recorded bus passes in white. Figure 3.12 shows that the electric bus produced sound energy focused around 8–9 kHz during its approach, with broadband sound up to approximately 14 kHz (ie, not focused at any particular frequency) recorded as it drew alongside the microphone. As the electric bus passed alongside and away from the microphone location, notable low frequency energy (1 kHz or less) was evident in the sound. The diesel bus also produced broadband sound during its approach and alongside the microphone (Figure 3.13). As the diesel bus moved away from the microphone, a notable modulating (increasing and decreasing) tonal component of sound was evident between 9 and 14 kHz. Overall, the frequency range of the two types of bus was very similar, but the nature of the sound within the frequency range differed between the two types of bus, as shown in Figure 3.12.

Figure 3.12 Spectrogram of a 30 km/h electric bus pass. Warmer colours indicate greater sound intensity, as per the colour bar. The bus sound is circled white.

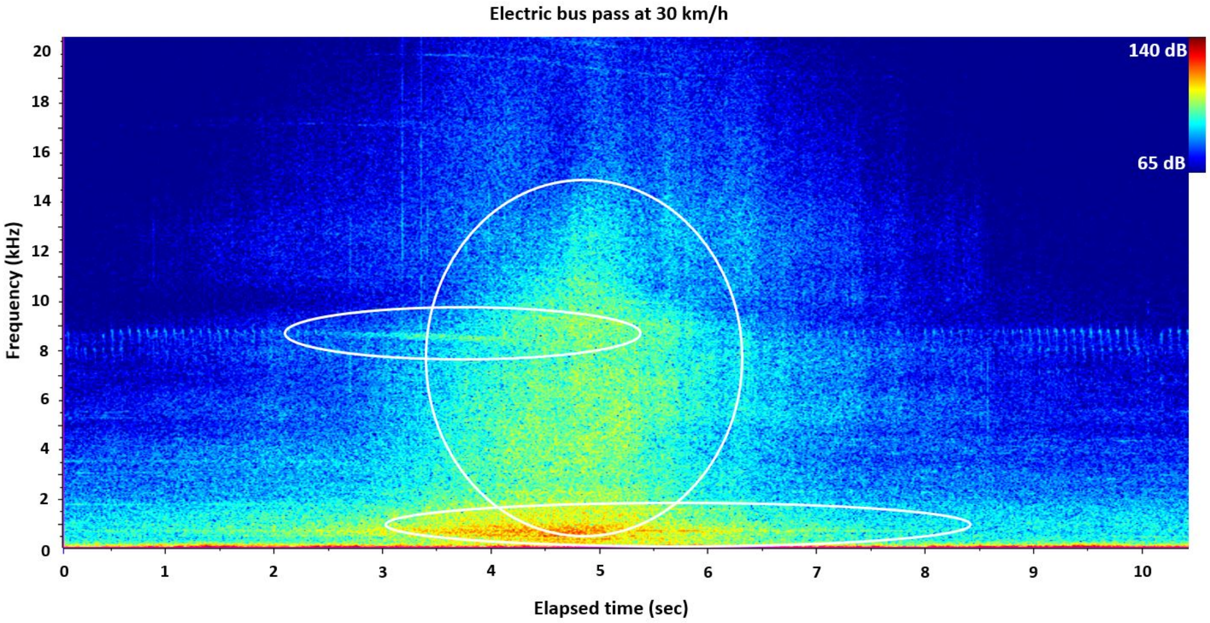
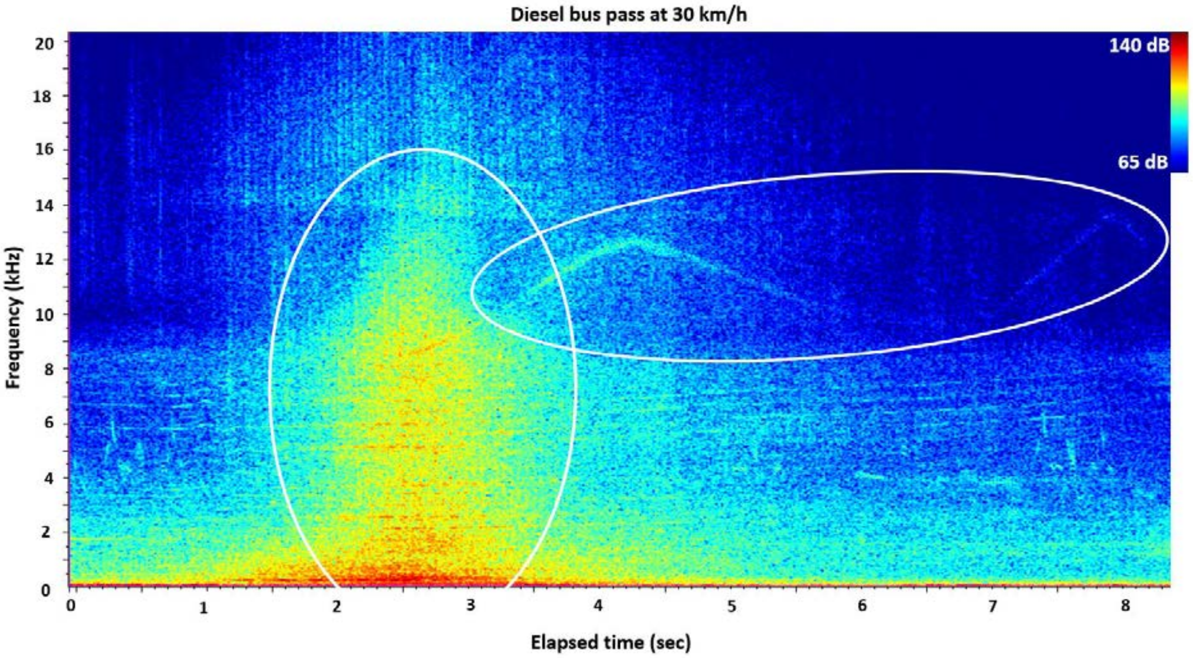


Figure 3.13 Spectrogram of a 30 km/h diesel bus pass. Warmer colours indicate greater sound intensity, as per the colour bar. The bus sound is circled white.

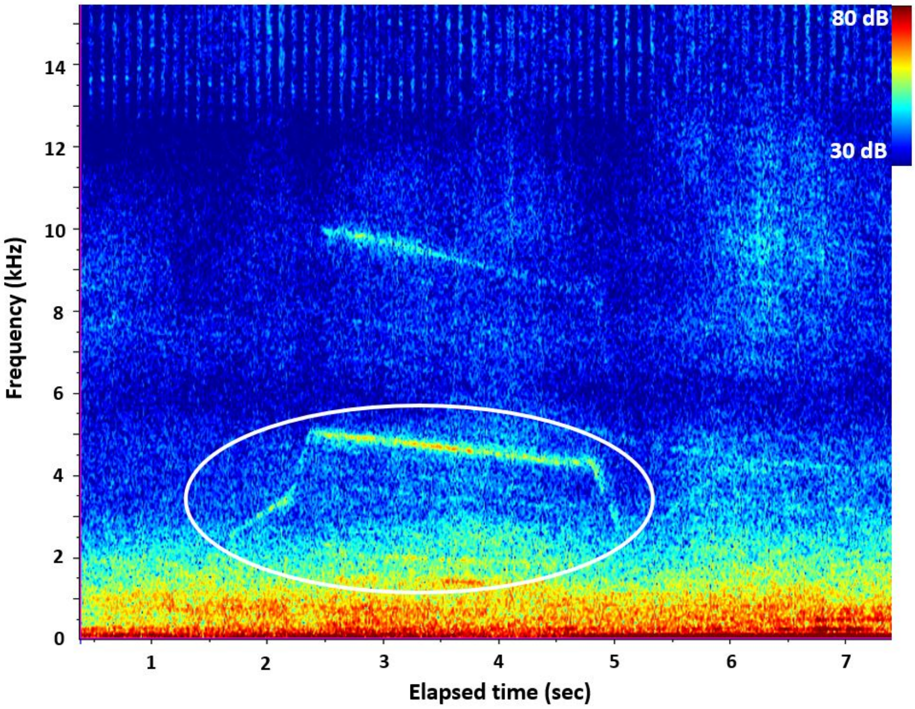


Sound energy by frequency – Specific noise

One of the most distinctive noises made by diesel buses was the retarder, which was most obvious when the bus was slowing or going downhill. A retarder, when activated, provides an auxiliary and independent braking system that reduces part of the kinetic energy of a decelerating bus.

Figure 3.14 illustrates the frequency information from a recording of a bus retarder from a non-target diesel bus that passed on the opposite side of the road in Wellington (going downhill). Most of the frequency content in this sound is between 4 and 5 kHz. The participants noted that this sound is very distinctive and is a good indication that the vehicle is a bus, as opposed to a truck or other heavy vehicle. The retarder sound was not generated by the target buses in Wellington because these buses were travelling uphill under power, and it was not noted at the Auckland survey site where buses were travelling on the flat at a slow speed.

Figure 3.14 Spectrogram of the distinctive retarder noise of a non-target bus passing downhill in Wellington (circled in white). Warmer colours indicate greater sound energy, as per the colour bar.



4 Discussion

Overall, our findings did not suggest a clear difference in detection distance or detectability between diesel and electric buses, with mixed results. In Auckland, diesel buses were more likely to be detected – and detected earlier – than electric buses, but there was considerable overlap in the data. In Wellington, the difference in detection was not significant according to bus type. However, the greatest detection distances were usually associated with diesel buses. These results broadly align with findings from the literature that electric buses are quieter than diesel buses below 30 km/h, which was the speed at which most buses in our testing passed participants.

The two testing locations were quite different environments. The Wellington site was very open, with ambient noise from other traffic, cicadas, and wind. On the other hand, the Auckland site was in the central city, surrounded by tall buildings, with multiple, complex noise sources in the environment. The ambient noise level at the Auckland location was approximately 3 dB louder than at the Wellington location. We suggest that the detectability of buses is not solely about the volume but also the quality of the sound. Busy urban environments are complex sound environments. It is not always straightforward for a person to distinguish the noise of a bus on an urban street.

We noted individual variation between the sensitivity of participants; some seemed able to detect buses at greater distances than others. In this sample, there did not appear to be substantial differences in detection distances between blind, low-vision and non-impaired participants.

Although there was a range of detection distances overall, participants' failure to detect the majority of electric buses in Auckland was an interesting finding. Over half of the electric buses in Auckland were not detected at all, while 87.5% of diesel buses were correctly detected. As mentioned, both bus types were detected more frequently when the sounds they made were either below or above ambient noise level. This finding may partially explain the differences in electric bus detection found between Auckland and Wellington. This finding also suggests that different sounds may be required in different environments.

However, we note that these failures may have been due to an inability to classify the noise as a bus, rather than an inability to detect the noise at all. That is, participants may have heard a vehicle but been unsure what it was. Detection and classification of sound are two separate events that must occur in order for a participant to raise their hand in our experiments.

The fact that some diesel buses were only detected after they had passed by may be the result of diesel bus design: the main noise sources (engine and exhaust) are located at the rear of diesel buses. In contrast, the main noise sources from electric buses seemed to be tyre/road noise (at speeds above 40 km/h) and general hydraulic noise associated with a heavy vehicle.

We did not report on the many false detections, where a participant raised their hand but there was no approaching bus. More false detections were made in Auckland due to other large vehicles on the road (such as trucks or fire engines), small vehicles on the road (SUVs, utes, and electric cars) and even electric scooters. In Wellington, where fewer false detections were made, they were primarily due to other large vehicles (such as trucks and a street sweeper), with only three false detections of small vehicles (sports cars). We assume that the high number of false detections in Auckland was due to complex sound reflections in the city centre street.

4.1 Implications for pedestrian safety

Results suggest that although there are some differences in the ways that people hear and detect electric buses compared with diesel buses, the differences are likely to be highly dependent on street context. Very few buses were missed in the Wellington test location compared with Auckland, which implies that any interventions (such as AVASs) that might be helpful in one location may not be necessary in another. However, AVASs still need to be tested in environments with poor baseline detection rates to prove their effectiveness.

For pedestrians crossing the street and particularly for the blind and low-vision community, safety when crossing a street requires auditory detection of vehicles and does not necessarily rely on the classification of the vehicle type. The risk of a pedestrian having a collision with a bus is a complex interaction of:

- pedestrian behaviour
- bus driver awareness
- bus traveling speed and ability to decelerate
- environmental factors such as visibility and the presence and suitability of road crossings.

While it appears that in some contexts electric buses are less likely to be detected than diesel buses (eg, our Auckland participant testing location), a direct link with increased crash risk cannot be made based solely on this research.

Results have demonstrated the complexity of bus detection in real street environments. This research has not arrived at a clear recommendation to add AVASs to electric buses. We suggest that further testing in a wider range of noise contexts is warranted before any policy recommendations are made concerning the addition of AVASs to buses (see section 5). Testing of different AVASs in different environments is needed too, as our results suggest the fit of the sound to the environment is important to detection.

4.2 Implications for bus detection by passengers

Passengers' ability to distinguish electric buses from other vehicles is important to consider for bus accessibility. For example, an individual waiting to board a bus needs to know when a bus is approaching. While AVASs are highly likely to help bus passengers recognise a bus (if they know what the sound means), there are other ways that buses can be detected that are not so invasive on the noise environment of a street (see section 5).

4.3 Research limitations

We acknowledge that the scope of this research and complications related to the COVID-19 pandemic limited our on-street exploration to a relatively small sample size of 14 participants. A higher number of participants and a broader range of street contexts would strengthen the results and enable stronger conclusions to be drawn.

A methodological limitation was our instruction to participants to raise their hand if they heard a bus. There was no recording of detecting other vehicles. If we had asked the participants to raise their hand when they heard any vehicle approaching, it is highly likely that the detection distances would have been larger than those reported here because any delay associated with classifying the sound as 'bus' or 'not bus' would have been removed. Further, in terms of pedestrian safety, it is more important that a pedestrian knows a vehicle is approaching than being able to discriminate whether or not it is a bus. Future on-street studies of this nature could adopt a two-hand system – for example, raising one hand for detecting a vehicle in the first instance, and raising the other hand to identify the vehicle as a bus.

5 Recommendations

We conclude that noises generated by both electric and diesel buses are part of a complex urban street environment. Based on the findings of our review of the literature and analysis of control and participant testing, we do not recommend that AVASs are immediately adopted as an intervention to improve pedestrian safety. Rather, it is recommended that this work is extended with more testing in a wider range of street contexts and for AVASs to be tested in locations where electric buses are less detectable.

In parallel with continued investigation of pedestrian safety on streets that include electric bus routes, we recommend collaboration with Transport for London to understand this issue in more depth. Recent on-street trials of AVASs may be available, and a workshop sharing findings from this research with relevant data from London would be useful to inform policy direction, and to highlight research gaps. Further research is also needed on annoyance caused by AVASs, as improvements to both safety and the soundscape are important outcomes.

5.1 Laboratory testing

On-street testing is affected by a large number of factors, many of which cannot be controlled. These include:

- weather conditions on the day of the testing (as discussed in the Wellington on-street testing results in relation to wind gusts)
- extraneous noise sources such as construction (as discussed in the controlled Auckland testing) and other vehicles (as discussed in the Auckland on-street testing)
- availability of test persons of a sufficient number and range (especially during the COVID-19 pandemic, which was ongoing throughout our research)
- bus timetables, which determine experiment length and therefore participant fatigue
- the availability of electric buses in different streetscapes (eg, suburban, urban or rural), which would enable testing over a wider range of ambient sound environments.

In a digital sound laboratory, these factors can be controlled to a much larger degree. To usefully extend this work, we recommend laboratory testing using ambient street noise, overlaid with the noises of electric and diesel buses, such as the noise captured in the control testing for this research.

5.2 Broader transport system recommendations

In terms of pedestrian safety, factors other than bus noise (or lack of noise) can be addressed somewhat through prioritised investment in safe street infrastructure. Speed management and high-quality pedestrian crossings that align with where pedestrians want to walk can help avoid situations where a pedestrian may cross oblivious of an approaching bus. Such interventions would improve safety for all road users, regardless of vehicle type.

It is also recommended that technology such as audible bus stop announcements and mobile phone applications are improved so that blind and low-vision bus passengers (in particular) can have confidence that their bus arrival is imminent. Working with the blind and low-vision community is important as new technologies are adopted so that people know what is available to them and so they have confidence completing journeys involving buses.

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Appendix A: Statistical test results

These data are the results of Chi-squared tests of independence for the relationship between engine type (electric or diesel) and participant detection of buses (1 and 2 below), and for the relationship between impairment and detection of buses (3 and 4 below). For tests 1 and 2, participants are combined and bus engine type is separated. For tests 3 and 4, participants are separated by impairment category and bus engine types are combined.

Early detection: Bus detected 5 m or more away from bus stop.

Late detection: Bus detected within 5 m of bus stop, or after it had passed the stop.

Detection: Bus was detected, even if it had already passed the stop.

No detection: Bus was not detected at all.

1. **Early vs late detection: all participants**

   Wellington: $\chi^2(1, 55) = 0.525$, $p = .469$, Cramér's V = 0.10

   Not significant: In Wellington there was no difference in detection by bus engine type.

   Auckland: $\chi^2(1, 95) = 8.876$, $p = .003$, Cramér's V = 0.31

   Significant: Participants in Auckland were more likely to detect a diesel bus early than an electric bus.

2. **Detection vs no detection: all participants**

   Wellington: There was not enough non-detection to test the difference between engine type.

   Auckland: $\chi^2(1, 128) = 25.959$, $p > .001$, Cramér's V = 0.45

   Significant: Participants in Auckland were more likely to detect a diesel bus than an electric bus.

3. **Early vs late detection: participant impairment**

   Wellington: $\chi^2(1, 55) = 0.009$, $p = 0.925$, Cramér's V = 0.01

   Not significant: There was no difference in bus detection distance by participant impairment type in Wellington.

   Auckland: $\chi^2(1, 95) = 5.079$, $p = 0.024$, Cramér's V = 0.23

   Significant: Participants in Auckland with good vision were more likely to detect a bus early than participants with low vision.

4. **Detection vs no detection: participant impairment**

   Auckland: $\chi^2(1, 128) = 0.137$, $p = 0.711$, Cramér's V = 0.03

   Not significant: Participants with good vision were no more likely to detect a bus than participants with low vision.