Road ecology practitioners, however, have tended to rely on traditional methodologies to measure negative impacts on wildlife, such as point-count surveys (PCS) (Magrath et al., 2010, Ralph et al., 1995, Loyn, 1986, Eyre et al., 2018). A 2022 review revealed many previous road ecology studies to be of low inferential strength, partly a result of the use of traditional methodologies (see Johnson *et al.*, 2022). New and innovative approaches, such as ***acoustic monitoring*** using ***autonomous recording units*** (ARUs), have been developed and used in several studies (Castro et al., 2019, Celis-Murillo et al., 2009, Darras et al., 2019, Stewart et al., 2020). Few studies, however, have documented this approach, especially the steps required to ensure an optimal experimental design tailored to their projects' requirements. Indeed, several studies within the recent literature appear to have relied on 'out-of-the-box' recorder settings to obtain data (but see Celis-Murillo *et al.*, 2009). This is a challenge for many studies as reliance on recorder factory settings, without performing field optimisation trials, may have compromised the outcomes of this research because of poor signal quality and incidence detection. So how does this field-of-research move forward?

The primary aim of this paper is to explore the innovative research methods used to design and develop a novel study approach for wildlife monitoring – paired acoustics surveys – in a road corridor. Specifically, this paper will document the approach used to design a ***before-after-control-investigation*** (BACI) study to examine the influence of the construction of a new major motorway on local birdlife in Southeast Queensland. This paper covers the background issues concerning data storage, power supply, sample period, microphone gain, signal integrity, recorder catchment, and target signal resolution, and the key methodologies that will be used. Documentation of this, and the processes through which each is established, will facilitate data collection, by transport scientists and practitioners alike, that, when integrated into an appropriate monitoring framework (see Johnson *et al.* 2022), achieves high inferential strength and contributes to positive road project outcomes (e.g., optimised placement location and construction of FSRD measures).

1.1 Point Count Surveys – the traditional approach to biodiversity monitoring

PCS is a widely used quantitative survey method where a single observer, stationed at a single point within a given area, records the number of birds detected over a standardised period (Loyn, 1986, Ralph et al., 1995, Bibby et al., 2000, Kulaga and Budka, 2019). Data derived from this technique can be used to measure biodiversity (i.e., species richness and abundance) (Loyn, 1986). Importantly, the procedure is highly flexible and can be modified to suit a range of experiments, species and conditions, and several methods have been derived and deployed (Bibby et al., 2000, BirdLife, 2021). There may, however, be several observer errors associated with this approach, including inaccurate bird position and distance measurements, species temporal and spatial detection probability, and observer influence on bird behaviour (Castro *et al.*, 2019; Kulaga & Budka, 2019). In addition to these, a range of other logistical (i.e., difficult terrain, equipment transport, weather) and/or financial (i.e., fuel for transport, accommodation, hiring of field staff) challenges may also be encountered in the application of PCS (Hao *et al.*, 2020).

1.2 Bioacoustic Monitoring – an alternative approach

Soundscape mapping (acoustic monitoring) is a new and valid approach that may be used to rapidly obtain and assess measures of biodiversity using acoustic indices, measured through ***biophony*** (animal sounds) and ***technophony*** (anthropogenic sounds) (Machado et al., 2017, Pankratz et al., 2017, Munro et al., 2018, Ducrettet et al., 2020, Hao et al., 2020). Songbirds are a very suitable target species for acoustic monitoring as they are acoustically oriented and rely heavily on call vocalisations in communication, territory defence, and courtship (Cuervo and Moller, 2020, Hawkins et al., 2020, Senzaki et al., 2020, Cooke et al., 2019, Grade and Sieving, 2016). Indeed, acoustic monitoring has been used to successfully quantify biodiversity, map forest soundscapes, and examine vocalisation quality and attributes following disturbance events (Machado et al., 2017, Pankratz et al., 2017, Munro et al., 2018, Khanaposhtani et al., 2019). This method can also improve data capture from species normally difficult to observe, thereby leading to enhanced conservation outcomes (Stewart et al., 2020, Ducrettet et al., 2020).

Similar to PCS, bioacoustic monitoring involves species/individual count data gathered from a single point in a pre-defined area but, using instead an autonomous recording unit (ARU) (Darras et al., 2019, Ericson et al., 2020, Stewart et al., 2020). ARUs are advantageous over PCI for a number of reasons. First, ARUs are capable of continuous and extended deployment within the field without the requirement for an observer(s) to be present (Abrahams, 2018, Ericson et al., 2020). Indeed, once installed, observer(s) are only required to access sites to obtain survey data – typically stored on a removable storage device (e.g., SD card) – and undertake recorder maintenance (i.e., inspect for damage, replace batteries, adjust recorder settings, etc.) (Abrahams, 2018, Ericson et al., 2020, Sedláček et al., 2015). Second, ARU deployment may also facilitate the collection of higher quality data; species may alter their vocalisations in response to human presence, and this may influence their probability of detection (Kulaga and Budka, 2019, Van Wilgenburg et al., 2017). This may be especially important where elusive and/or rare species are the focus of monitoring (Stewart et al., 2020, Ducrettet et al., 2020). Finally, ARUs create a permanent record of each survey, which allows observers to re-examine recordings multiple times to assist with species identification (Sedláček et al., 2015, Abrahams, 2018, Bombaci and Pejchar, 2018). This may also prove useful in the event of project handover, especially where longer-term projects are involved (Ericson et al., 2020). Overall, bioacoustics surveys are capable of outperforming traditional surveys (e.g., PCS) using human observers.

To date, however, relatively few studies that use the acoustic monitoring approach are published (Johnson *et al*., 2022). This may be due to unfamiliarity with the procedure, substantial upfront and ongoing costs, risk of equipment theft/damage/failure, and requirement for data storage (Stewart et al., 2020, Ericson et al., 2020). Indeed, practitioners need to ensure ARUs selected for field deployment are constructed of high-quality materials and are capable of accurately recognising the target species (Ericson et al., 2020, Abrahams, 2018). Depending on the study, ARUs may also need to be able to distinguish between individuals (Ericson et al., 2020). Moreover, trained observers are required to listen to recordings and code each for weather, quality, and species, which can be a tedious process (Khanaposhtani et al., 2019, Ericson et al., 2020, Hao et al., 2020). Commercial software is available and can be used to quickly inspect audio files for species of interest but may be difficult to operate without prior training and experience (Ericson et al., 2020).

2. Bioacoustic Monitoring – an alternative approach

Species lists were initially developed from a series of PCSs conducted at the research sites between October 2021 – February 2022. A total of 65 species were recorded at both Careel Reserve (56) and Coombabah Creek (48) (see supplementary material). From this list, eight species were selected for ongoing monitoring and analysis: mistletoebird (*Dicaeum hirundinaceum*), grey fantail (*Rhipidura albiscapa*), scarlet myzomela (*Myzomela sanguinolenta*), leaden flycatcher (*Myiagra rubecula*), rufous whistler (*Pachycephala rufiventris*), eastern yellow robin (*Eopsaltria australis*), grey shrike-thrush (*Colluricincla harmonica*), and noisy friarbird (*Philemon corniculatus*). These species are broadly considered to be common within urban habitats and were recorded in all PCSs undertaken during the initial survey period. Importantly, these species are suitable for bioacoustic surveys as each frequently produces loud, repetitive, and stereotyped calls – high energy vocalisations used in broadcasts (i.e., for communication) – as opposed to songs – low energy vocalisations used in mate attraction and breeding. Table 1 provides further detail on the vocalisations of interest.

Table 1 – Target species and their vocal characteristics

Species	Vocalisation	Description
Mistletoebird (*Dicaeum hirundinaceum*)	Twitch	Clear, high-pitched, carrying: ‘ti-wich’ / ‘tee-wietch’
Grey fantail (*Rhipidura albiscapa*)	Cascading chatter	A cheery outpouring of high and low chatterings: ‘twitch-twitchit’ / ‘tsweeit-tseet’ / ‘chit-wit’
Scarlet myzomela (*Myzomela sanguinolenta*)	Harmonic twitter	Descending ‘teeee-tee tidi tidi’
Leaden flycatcher (*Myiagra rubecula*)	Repetitive whistle	Clear carrying ‘whit-ee-eight’ / ‘whee-ity’
	Scissor cut	Harsh, nasal buzzing ‘tzzeep’ / scrzzarch’
Rufous whistler (*Pachycephala rufiventris*)	Whistle	Long, loud, rapid succession or ringing notes without pause: cheWIT-chWit-chWIT-chWIT
	Whipcrack	Call with high, thin, drawn-out beginning and powerful, ringing whipcrack finish: ‘eeee-CHIEW’ / ‘eeee-CHONG’
Eastern yellow robin (*Eopsaltria australis*)	Repetitive chew	Repeated, clear, even, loud piping whistle: ‘tchiep’
	Double chew	‘tchweip-tchweip’
Grey shrike-thrush (*Colluricincla harmonica*)	Whistle-ring	Repetitive mellow throaty ring rising to high, clear ringing whistke: ‘chew-chew-ccheeew WHIEET-CHIEW’
Noisy friarbird (*Philemon corniculatus*)	Rollicking honk	Deep, loud and repeated goose-like honk: ‘owk-orrok’
	Metallic honk	Very loud, sharp, metallic: ‘owk’

Finally, all eight species are recognised as indicators of an intact ***Temperate and Subtropical Woodland Bird Community*** (TSWBC) (see Fraser *et al.* 2019). Although members of this community are regarded to be relatively common, research has shown the broader community (the TSWBC) has undergone significant decline in geographic range (Fraser et al., 2019). In particular, the sub-community in Southeast Queensland, the *Subtropical Queensland Community*, is threatened by loss of functionally important species as well as reduced community integrity (Fraser et al., 2019). Indeed, the rate of continuing detrimental change to this community meets criteria for ‘Critically Endangered’ status under the *Environment Protection and Biodiversity Conservation Act 1999* (Fraser et al., 2019). Importantly, small birds (<50g) comprise a large proportion of the TSWBC) (Fraser et al., 2019). The occurrence and movement of small birds in Australia, many of which comprise the TSWBC, are known to be highly susceptible to the road effect zone (Johnson et al., 2017, Pell and Jones, 2015).

2.1 Recorder Selection

Several recording devices are available, such as hand-held and specialty recorders (Bombaci and Pejchar, 2018, Celis-Murillo et al., 2009), although the preferred approach is to use 'off-the-shelf' single recorder units (Abrahams, 2018). This experiment used the Wildlife Acoustics Song Meter (SM) Mini. The SM Mini is a small and lightweight recorder that features one built-in omni-directional microphone, with the option for an additional microphone for stereo recordings. The built-in microphone(s) possesses a sensitivity of -7.0 ± 4dB and a signal-to-noise ratio of 78 dB at 1kHz. The SM Mini was chosen on the merits of its cost-effectiveness. SM Minis are a less expensive option, compared other high-end devices, such as the SM4, with comparable audio quality (Wildlife Acoustics, 2022). Previous studies have used other devices and technologies that have since become obsolete, such as the SM2 and SM3 recorders (Kulaga and Budka, 2019, Van Wilgenburg et al., 2017, Stewart et al., 2020), or were less likely to produce audio files of suitable quality for automatic signal detection (Bombaci and Pejchar, 2018).

2.2 Sample Effort and Timing

ARU settings were determined from an initial 14-day pilot study in October 2021. The purpose of these trials was to establish optimal study design through experimental manipulation of data storage, power supply, sample period, microphone gain, signal integrity, recorder catchment, and target signal resolution. Four ARUs were installed across two transects, two recorders along each (1x 'near' and 1x 'far'), in Careel Reserve, Nerang. All recorders were installed at locations with a minimum separation of 150m distance, between devices, to ensure independent counts (Abrahams, 2018). Microphone gain (i.e., microphone sensitivity) was set to 31dB and 37dB along Transect 1 and Transect 2 respectively. Standard audio settings for bird surveys were used: PCM.wav files using 44,100kH sample rate and 16-bit depth. For the purposes of this experiment, ARUs were set to record continuously (i.e., 24hrs/day) over the 14-day period. Song Meter Minis require four (4) AA batteries to operate: alkaline batteries were used during the initial 7-days, while lithium-ion batteries were used for the final 7-days. A maintenance visit was performed at Day 5 and 10 to replace batteries (Alkaline → Lithium-ion) and memory storage (SanDisk XC Extreme Plus 150Mb/s 128Gb) and check recorder functionality.

2.3 Recorder Catchment

Microphone catchment and gain trials were performed in a series of follow-up paired acoustic surveys between January-February 2022. These were modified from two earlier studies (Darras et al., 2018, Darras et al., 2016), and informed by the *Designing Effective Bioacoustic Studies* course delivered in Brisbane (Frontiers Labs, 2022).

Three SM Minis, one each of 25, 31 and 37dB microphone gain, were set to record continuously and secured to one another using duct tape. The observer then performed a series of 20-minute paired acoustic surveys, during which all signals produced by target species were identified. During this time, the observer was situated 5 meters from the recorders. Once located and identified, the distance between the bird and the observer was measured using a handheld Nikon Forestry Pro laser rangefinder. Where distance could not be measured to the point of origin (e.g., dense vegetation), distance to the tree trunk nearest to the point of origin was used. The final distance measured was then recorded aurally.

Recordings were then examined both holistically (at a whole of recording level) and specifically (at instances of focal signals) using Audacity 3.1.3 (CMake Release build Dec 2021, 64 bits). ***Signal-to-noise ratio*** (SN ratio) was then determined through visual measurement of the difference between the target signal and background noise using the 'Plot Spectrum' function in Audacity. The resultant SN ratio over distance from the observer (m) was then graphically displayed to visualise the recorder catchment distance for each of the species captured. The optimal microphone gain, that balanced signal integrity and the effects and frequency of signal clipping – noise that exceeded microphone capacity, thereby making the signal unavailable for detection – was then selected.

2.4 Automated Signal Detection

An advanced detection classifier was developed using Kaleidoscope Pro to process audio recordings obtained over the initial 14-day pilot study in October 2021. Kaleidoscope Pro audio analysis software is capable of batch analysis of audio recordings into clusters of similar recordings, which the software assumes to be similar species (Ericson et al., 2020, Abrahams, 2018). Audio clustering was performed using the settings recommended by the manufacturer: 0.35 second inter-syllable gap, 2,500-10,000 Hz frequency range, and a detection length range of 0.1-7.5 seconds. The observer visually scanned, played, and labelled audio files produced following cluster analysis. Only high-quality recordings in which the target species vocalisations (see Table 1) could be observed clearly, with minimal interference from background noise, were labelled for use in audio recognition (Ericson et al., 2020). This created a new cluster list, saved in CSV file format, that was then used to perform another cluster analysis of the same data. This was repeated multiple times to produce an advanced classifier capable of reliably and accurately detecting and labelling vocalisations of the target species.

3. Results

3.1 Power Supply and Data Storage

Operational lifespan of ARUs, programmed for continuous recording, was approximately 5-days using 4x AA alkaline batteries and >10-days when using 4x AA lithium-ion batteries. Maximum data storage capacity was achieved after approximately 7-days when using an 128 Gb 150MB/s *Extreme Plus* SD card.

3.2 Sample Effort and Intensity

Analysis of the recordings from the initial 14-day pilot study, using Kaleidoscope Pro, identified 84,601 vocalisations. Two periods of high activity were observed: morning (0500 and 1100 hours) and early/mid-afternoon (1300 to 1500 hours) (Figure 1). Importantly, 21,799 vocalisations were produced by seven of the eight target species.

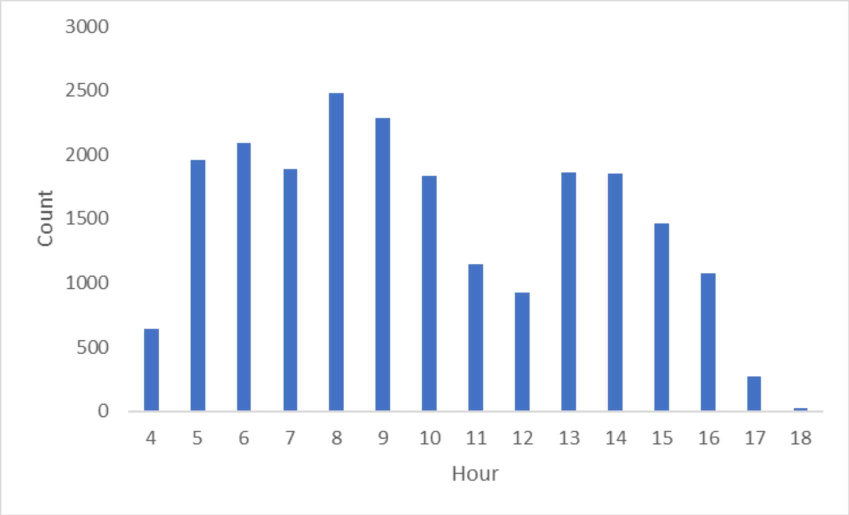


Figure 1 – mean avian vocal activity over a 14-day period

3.3 Recorder Catchment

The signal-to-noise ratio (SN ratio) was quantified for four species: mistletoebird, grey fantail, rufous whistler, and grey shrike-thrush. Despite consistent variability both within and between species, plotted SN ratios revealed each of the four species captured were generally detectable within a 50-100m distance from the ARUs.

SN ratios of Mistletoebird vocalisations decline substantially within 50m distance of the ARUs: SN ratio declined from ~20 at <20m distance to ~7 at 40-50m distance (Figure 2). Mistletoebird vocalisations were not detected by ARUs beyond 50m distance. Overall, a microphone gain setting of 31dB improved signal detection, amongst background noise, compared to 25dB and 37dB microphone gains (Table 2).

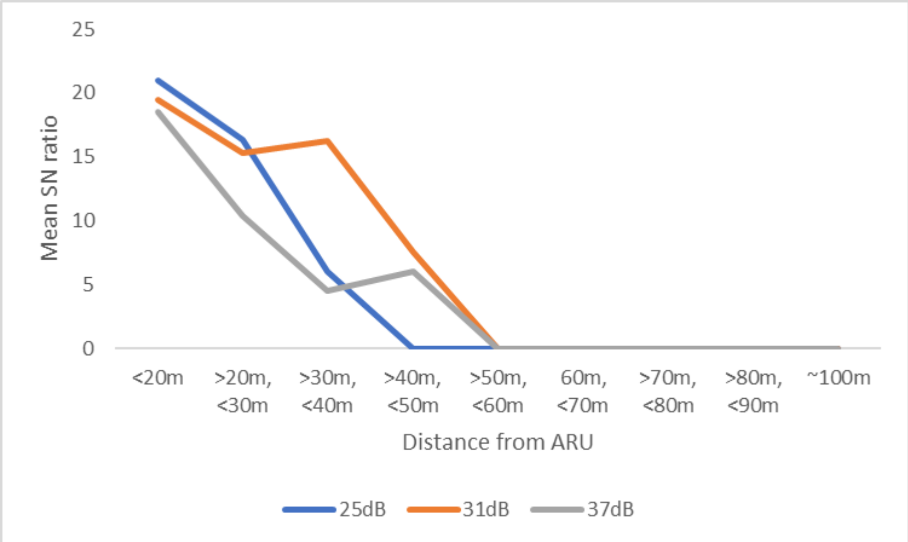
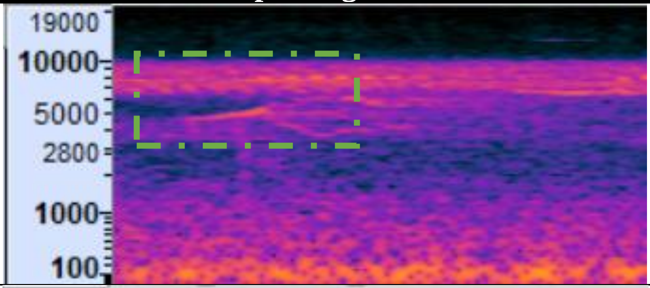
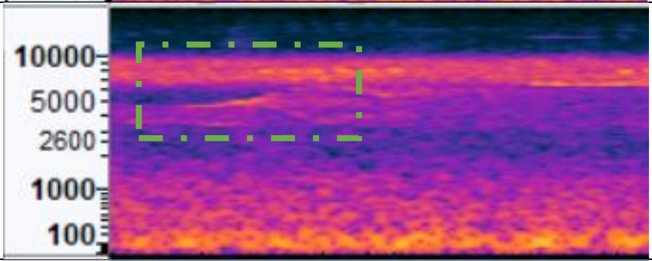
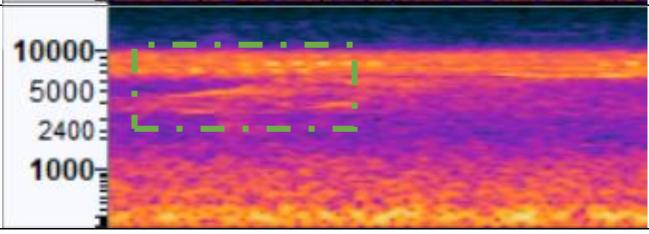


Figure 2 – Mean signal detection of mistletoebird

Table 2 – Spectrograms of the same mistletoebird '*twitch*' call (green box) detected at 28 meters using different microphone gain settings. Note how the signal is visible at 25 dB gain, is enhanced slightly at 31 dB gain, but becomes obscured by background (pink) noise at 37 dB gain. Although still visible in the latter, the signal is now unsuitable for audio analysis as it is indistinguishable from the background noise.

Microphone gain setting	Spectrogram
25 dB	
31 dB	
37 dB	

SN ratios of grey fantail vocalisations decline substantially within 60m distance of the ARUs: SN ratio declined substantially beyond 40m distance (Figure 3). Grey fantail vocalisations were not detected by ARUs beyond 60m distance. Overall, a microphone gain setting of 31dB resulted in improved signal detection, compared to 25dB and 37dB.

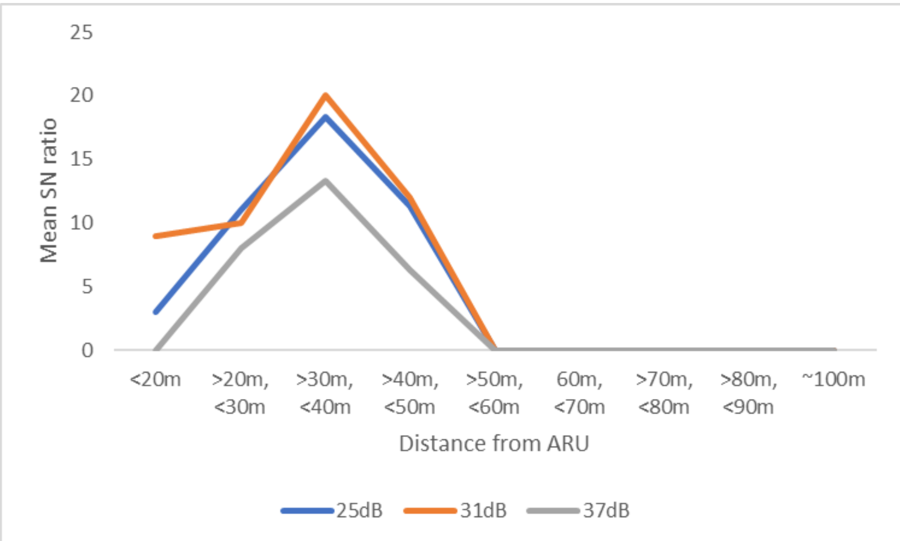


Figure 3 – Mean signal detection of grey fantail

SN ratios of rufous whistler vocalisations displayed substantial variability within 90m, but generally declined substantially beyond 80m distance (Figure 4). Rufous whistler vocalisations were not detected by ARUs beyond 90m distance. Overall, a microphone gain setting of 31dB resulted in improved signal detection, compared to 25dB and 37dB.

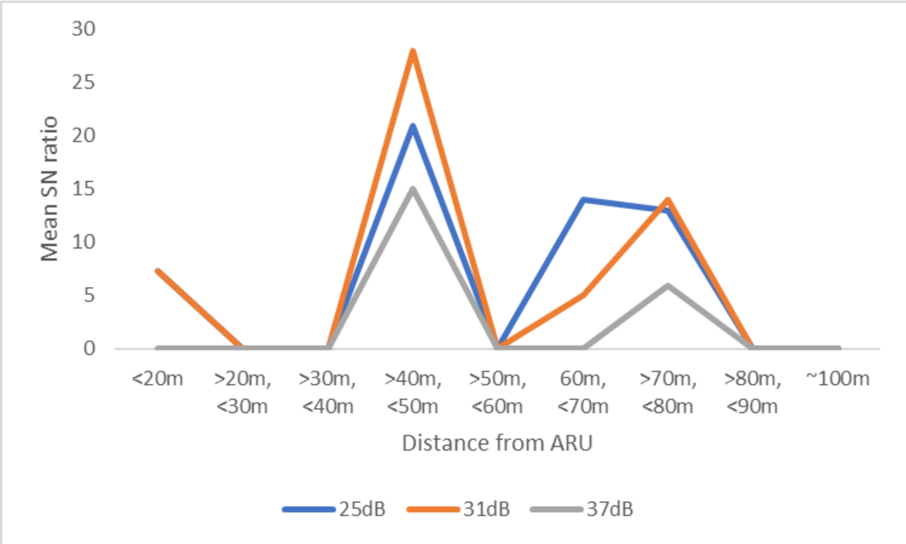


Figure 4 – Mean signal detection of rufous whistler

SN ratios of grey shrike-thrush displayed no decline within 100m distance of ARUs (Figure 5). Overall, a microphone gain setting of 31dB resulted in improved signal detection, compared to 25dB and 37dB.

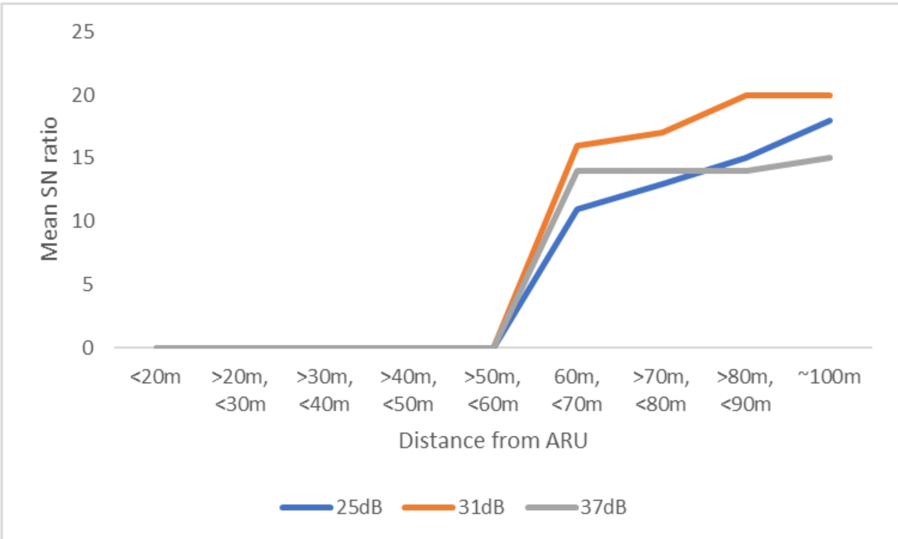


Figure 5 – Mean signal detection of grey shrike-thrush

SN ratios for the remaining four species: scarlet myzomela, eastern yellow robin, leaden flycatcher, and noisy friarbird; could not be calculated due to the limited datasets constructed from field surveys. At least two records, however, exist for each of these species and indicate vocalisations to be detectable within 50-100m of the ARUs: scarlet myzomela (≤70m), leaden flycatcher (≤60m), eastern yellow robin (≤100m), and noisy friarbird (≤70m). Preliminary field measurements, combined with prior experience of species ecology, suggest similar patterns to the above – i.e., individuals are detectable within 50-100m distance of ARUs.

4. Final Study Design

In general, the methodology for avian acoustic surveys will be adapted from recent avian acoustic studies (Stewart et al., 2020, Hao et al., 2020, Khanaposhtani et al., 2019) and modified to incorporate the Johnson *et al.* (2022) framework for measuring the impacts of roads on birds (and other wildlife). Ten ***autonomous recording units*** (ARUs) (Song Meter Mini Wildlife Acoustics with two omnidirectional microphones; signal-to-noise ratio 78dB at 1kHz) will be deployed along five transects across three bushland study sites for the duration of the experiment (2021-2026). In each transect, two (2) ARUs will be installed in trees, at approximately 180cm height, at two different distances perpendicular to the vehicle or non-vehicle gap: 'near' ARUs at <50m and 'far' ARUs at ~250m. This design will enable varied exposure to construction- and traffic-generated noise throughout the experimental period. All ARUs will be separated by a minimum of 200m to ensure spatial independence. This was informed by the grey shrike thrush, the target species with the greatest acoustic footprint (~100m) (Figure 5).

A stratified 'on-off' sample approach will be used. ARUs will be programmed to capture 20 minutes of audio at the top of each hour between 0800 to 1100 (AEST +10) every 14-days – preliminary surveys revealed greatest call detection occurred within this timeframe (Figure 1). Stratification of bioacoustic surveys is known to result in a dataset of comparable quality to continuous recordings (Abrahams, 2018). Survey effort during the dawn chorus was avoided due to poor signal detection from simultaneous vocalisations of multiple species – positive identification by automatic signal detection (i.e., Kaleidoscope) is substantially reduced during this period (Bombaci and Pejchar, 2018, Ericson et al., 2020). All recordings will be made in stereo using an uncompressed .wav file format at a sample rate of 44.1 kHz. A microphone gain setting of 31 dB was selected as this generally resulted in greater S/N ratios (Figures 2-5) and greatest signal clarity (Table 2). Using these settings, operational lifespan of a single SM Mini ARU is calculated to be approximately 9-months, using 4x AA lithium-ion batteries. Maximum data storage capacity, using 128 Gb 150MB/s *Extreme Plus* SD card, will also attained after approximately 3-years.

Presence of each of the eight target species in the road corridor will be confirmed through use of the advanced classifier constructed in Kaleidoscope Pro. Standard cluster analysis settings recommended by Wildlife Acoustics will be retained in the present study: inter-syllable gap of 0.35 seconds, syllable frequency between 250-10,000 Hz, and length of detection between 0.1-7.5 seconds. Rainy and windy recordings, as well as recordings of other non-target species (i.e., non-birds), will be excluded from further analysis.

Traditional point-count surveys (PCS) will be used to sample bird communities at each bushland site. PCS will be timed to coincide with acoustic surveys – observations over a 20-minute period between 0800 and 1100 (AEST +10). During these, the observer(s) will be stationed at a point near the ARU (~5m) and record all new observations and/or vocalizations of the eight species of interest within the specified time limit (i.e., 20-minutes). Unlike bioacoustics surveys, target species do not necessarily need to be heard to be present within the PCS survey. To ensure adequate statistical power, each ARU location will be surveyed once monthly, as a minimum, throughout the study period (2022-2026).

5. Final Comments and Considerations

The outcomes of this pilot study were five-fold, providing ways for other road ecologists to harness these methods. First, 128Gb SD cards were appropriate and achieved adequate data storage for the volume of data collected. Second, lithium-ion compared to alkaline AA batteries offered greater reliability in terms of ARU operation (>10-days vs. 5-days). Third, SM Minis, with the help of Kaleidoscope Pro software, reliably detected vocalisations produced by seven of the eight target species. Moreover, species were detectable under the microphone gains applied in this trial (31dB and 37dB). Fourth, a graphical display of all bird vocalisations revealed 0500-1100 to be a period of high signal activity; sample effort within this period would thus likely yield a representative dataset for the site. Finally, 31dB microphone gain proved to be the most optimal of the three recorder settings and balanced signal detection and audio clarity of the target species to distances up to 100m.

Several limitations were, however, apparent in the present study and should be carefully considered by prospective users of these technologies. First, users should carefully consider ARU quality, especially the composite materials used, as this may have substantial bearing on data collection and quality. The present study used the Wildlife Acoustics SM Mini and these generally performed to a satisfactory standard in the present study. One device, however, did malfunction approximately 5-days into the pilot study after a significant rainfall event. A routine maintenance inspection on the 7th day identified water build-up within the device, suggesting a failure of the lid's water-tight seal. It is noted in the manufacturer's manual that the 'snap-on' lid may not form a water-tight seal if the ARU is secured too tightly, via the mounting flanges on the main body, to a mount (Wildlife Acoustics, 2022). All ARUs used in the present study were loosely secured to tree trunks to avoid this. Irrespective, this malfunction resulted in 2-days of lost survey effort and necessitated removal of the ARU from the field, resulting in an additional 7-days of lost survey potential for that site.

Second, pilot studies using these devices should be performed over a 3-month period, during which time researchers should aim to undertake the greatest survey effort feasible (Pedersen, 2022). Survey effort in the present study was concentrated over a 14-day period due to several time constraints, in particular the requirement to quickly commence baseline data collection prior to highway construction in mid-2022. This resulted in a relatively small dataset from which to calculate ARU catchments. Indeed, while seven of the eight target species were detected within the present study, ARU catchments could only be reliably calculated for four of the species detected. Greater survey effort over an extended period may have improved species probability of detection, especially of seasonally transient species such as the scarlet myzomela and leaden flycatcher. Moreover, survey effort over greater time scales may also have enhanced the capture of temporal and spatial variations in species vocal repertoire, for example breeding vs. non-breeding, which can improve precision of automatic signal detection software (Abrahams, 2018, Ericson et al., 2020).

Finally, this study did not report on identification error rates that resulted from automatic signal detection software. This is an important requirement of any study that applies this technology (Abrahams, 2018). The advanced classifier, constructed in Kaleidoscope Pro, will be applied to the baseline data currently being collected. This will be explored in future publications.

Paired acoustics surveys are a new methodology at the very forefront of the field. They can enhance projects that seek to monitor road impacts on a broad array of wildlife, especially birds, through facilitating collection of higher quality data. Consequently, this would be of considerable value to road transport engineers as such an approach would facilitate improved road infrastructure planning and design, especially fauna-sensitive road design (FSRD) measures. Such experiments, however, require careful planning and design to implement effectively. The methodology documented in this paper offers road ecology researchers and practitioners a relatively simple and inexpensive approach to designing a wildlife survey protocol for use in road transport projects. In time, this will facilitate enhancement of targeted interventions that mitigate road impacts on wildlife.

6. References

ABRAHAMS, C. 2018. Bird bioacoustic surveys - developing a standard protocol. *In Practice,* 102**,** 20-23.

BIBBY, C., JONES, M. & MARSDEN, S. 2000. Expedition Field Techniques - Bird Surveys. Wellbrook Court, Girton Road, Cambridge: BirdLife international.

BIRDLIFE. 2021. *Survey Techniques Guide* [Online]. BirdLife Australia. Available: https://birdata.birdlife.org.au/survey-techniques [Accessed].

BOMBACI, S. & PEJCHAR, L. 2018. Using paired acoustic sampling to enhance population monitoring of New Zealand's forest birds. *New Zealand Journal of Ecology*.

CASTRO, I., DE ROSA, A., PRIYADARSHANI, N., BRADBURY, L. & MARSLAND, S. 2019. Experimental test of birdcall detection by autonomous recorder units and by human observers using broadcast. *Ecol Evol,* 9**,** 2376-2397.

CELIS-MURILLO, A., DEPPE, J. L. & ALLEN, M. F. 2009. Using soundscape recordings to estimate bird species abundance, richness, and composition. *Journal of field ornithology,* 80**,** 64-78.

COOKE, S. C., BALMFORD, A., JOHNSTON, A., MASSIMINO, D., NEWSON, S. E. & DONALD, P. F. 2019. Road exposure and the detectability of birds in field surveys. *Ibis*.

CUERVO, J. J. & MOLLER, A. P. 2020. Demographic, ecological, and life-history traits associated with bird population response to landscape fragmentation in Europe. *Landscape Ecology,* 35**,** 469-481.

DARRAS, K., BATARY, P., FURNAS, B. J., GRASS, I., MULYANI, Y. A. & TSCHARNTKE, T. 2019. Autonomous sound recording outperforms human observation for sampling birds_a systematic map and user guide. *Ecological Applications,* 29**,** 1247-1265.

DARRAS, K., FURNAS, B., FITRIAWAN, I., MULYANI, Y., TSCHARNTKE, T. & REYNOLDS, J. 2018. Estimating bird detection distances in sound recordings for standardizing detection ranges and distance sampling. *Methods in Ecology and Evolution,* 9**,** 1928-1938.

DARRAS, K., PÜTZ, P., FAHRURROZI, REMBOLD, K. & TSCHARNTKE, T. 2016. Measuring sound detection spaces for acoustic animal sampling and monitoring. *Biological Conservation,* 201**,** 29-37.

DUCRETTET, M., FORGET, P.-M., ULLOA, J. S., YGUEL, B., GAUCHER, P., PRINCÉ, K., HAUPERT, S. & SUEUR, J. 2020. Monitoring canopy bird activity in disturbed landscapes with automatic recorders: A case study in the tropics. *Biological Conservation,* 245**,** 108574.

ERICSON, M., HIRON, M. & HARTMAN, G. 2020. Evaluation of wildlife acoustic survey as a method to estimate bird habitat quality. Uppsala: Swedish University of Agricultural Sciences.

EYRE, T. J., FERGUSON, D. J., HOURIGAN, C. L., SMITH, G. C., MATHIESON, M. T., KELLY, A. L., VENZ, M. F., HOGAN, L. D. & ROWLAND, J. 2018. Terrestrial Vertebrate Fauna Survey Guidelines for Queensland. *In:* SCIENCE, D. O. E. A. (ed.) 3 ed. Brisbane: Queensland Government, Brisbane.

FORMAN, R. T. T. & DEBLINGER, R. D. 2000. The Ecological Road-Effect Zone of a Massachusetts (U.S.A.) Suburban Highway. *Conservation Biology,* 14**,** 36-46.

FORMAN, R. T. T., REINEKING, B. & HERSPERGER, A. M. 2002. Road Traffic and Nearby Grassland Bird Patterns in a Suburbanizing Landscape. *Environmental Management,* 29**,** 782-800.

FRASER, H., SIMMONDS, J. S., KUTT, A. S. & MARON, M. 2019. Systematic definition of threatened fauna communities is critical to their conservation. *Diversity and Distributions,* 25**,** 462-477.

GRADE, A. M. & SIEVING, K. E. 2016. When the birds go unheard: highway noise disrupts information transfer between bird species. *Biology Letters,* 12**,** 4.

HAO, Z., WANG, C., SUN, Z., VAN DEN BOSCH, C. K., ZHAO, D., SUN, B., XU, X., BIAN, Q., BAI, Z., WEI, K., ZHAO, Y. & PEI, N. 2020. Soundscape mapping for spatial-temporal estimate on bird activities in urban forests. *Urban Forestry & Urban Greening***,** 126822.

HAWKINS, C. E., RITROVATO, I. T. & SWADDLE, J. P. 2020. Traffic noise alters individual social connectivity, but not space-use, of Red-backed Fairywrens. *Emu*.

JOHNSON, C. D., EVANS, D. & JONES, D. 2017. Birds and Roads: Reduced Transit for Smaller Species over Roads within an Urban Environment. *Frontiers in Ecology and Evolution,* 5**,** 10.

JOHNSON, C., JONES, D., MATTHEWS, T., & BURKE, M. 2022. Advancing avian road ecology research through systematic review. *Transportation Research Part D: Transport and Environment, 109*. doi:10.1016/j.trd.2022.103375

JONES, BAKKER, BICHET, COUTTS & WEARING 2010. Restoring Connectivity over Compton Road: Assessing recreated habitat on the land-bridge - A Report for Brisbane CIty Council. Environmental Futures Centre: Griffith University.

JONES, D. & BOND, A. 2010. Road barrier effect on small birds removed by vegetated overpass in South East Queensland. *Ecological Management & Restoration,* 11**,** 65-67.

KHANAPOSHTANI, M. G., GASC, A., FRANCOMANO, D., VILLANUEVA-RIVERA, L. J., JUNG, J. H., MOSSMAN, M. J. & PIJANOWSKI, B. C. 2019. Effects of highways on bird distribution and soundscape diversity around Aldo Leopold's shack in Baraboo, Wisconsin, USA. *Landscape and Urban Planning,* 192**,** 13.

KOCIOLEK, A., GRILO, C. & JACOBSON, S. 2015. Flight Doesn't Solve Everything: Mitigation of Road Impacts on Birds. *Handbook of Road Ecology.* wiley.

KULAGA, K. & BUDKA, M. 2019. Bird species detection by an observer and an autonomous sound recorder in two different environments: Forest and farmland. *PLoS One,* 14**,** e0211970.

LOYN, R. 1986. The 20 minute search - A simple method for counting forest birds. *Corella,* 10**,** 58-60.

MACHADO, R. B., AGUIAR, L. & JONES, G. 2017. Do acoustic indices reflect the characteristics of bird communities in the savannas of Central Brazil? *Landscape and Urban Planning,* 162**,** 36-43.

MAGRATH, M., WESTON, M., OLSEN, P., ANTOS, M. & HERROD, A. 2010. Survey guidelines for Australia's threatened birds. *In:* DEPARTMENT OF THE ENVIRONMENT, W., HERITAGE, AND THE ARTS (ed.) *Guidelines for detecting birds listed as threatened under the Environment Protection and Biodiversity Conservation Act 1999.* Canberra: Australian Government.

MUNRO, J., WILLIAMSON, I. & FULLER, S. 2018. Traffic noise impacts on urban forest soundscapes in south-eastern Australia. *Austral Ecology,* 43**,** 180-190.

PANKRATZ, R. F., HACHE, S., SOLYMOS, P. & BAYNE, E. M. 2017. Potential benefits of augmenting road-based breeding bird surveys with autonomous recordings. *Avian Conservation and Ecology,* 12**,** 22.

PEDERSEN, T. (2022). Short course entitled *Designing Effective Bioacoustic Studies*. Frontier Labs. Brisbane. Qld. 16th-18th March.

PELL, S. & JONES, D. 2015. Are wildlife overpasses of conservation value for birds? A study in Australian sub-tropical forest, with wider implications. *Biological Conservation,* 184**,** 300-309.

RALPH, C. J., SAUER, J. R. & DROEGE, S. 1995. Monitoring bird populations by point counts. *In:* DEPARTMENT OF AGRICULTURE, F. S., PACIFIC SOUTHWEST RESEARCH STATION. (ed.). Albany, California, USA: Department of Agriculture, Forest Service, Pacific Southwest Research Station.

SEDLÁČEK, O., VOKURKOVÁ, J., FERENC, M., DJOMO, E. N., ALBRECHT, T. & HOŘÁK, D. 2015. A comparison of point counts with a new acoustic sampling method: a case study of a bird community from the montane forests of Mount Cameroon. *Ostrich,* 86**,** 213-220.

SENZAKI, M., KADOYA, T. & FRANCIS, C. D. 2020. Direct and indirect effects of noise pollution alter biological communities in and near noise-exposed environments. *Proceedings of the Royal Society B: Biological Sciences,* 287.

STEWART, L. N., TOZER, D. C., MCMANUS, J. M., BERRIGAN, L. E. & DRAKE, K. L. 2020. Integrating wetland bird point count data from humans and acoustic recorders. *Avian Conservation and Ecology,* 15**,** 1-22.

VAN DER REE, R., SMITH, D. & GRILO, C. 2015. The Ecological Effects of Linear Infrastructure and Traffic: Challenges and Opportunities of Rapid Global Growth. *In:* VAN DER REE, R., SMITH, D. & GRILO, C. (eds.) *Handbook of Road Ecology.* 2 ed. West Sussex: John Wiley & Sons, Ltd.

VAN WILGENBURG, S. L., SÓLYMOS, P., KARDYNAL, K. J. & FREY, M. D. 2017. Paired sampling standardizes point count data from humans and acoustic recorders. *Avian Conservation and Ecology,* 12.

WILDLIFE ACOUSTICS. 2022. Song Meter Mini – User Guide.

WILSON, R. F., MARSH, H. & WINTER, J. 2007. Importance of canopy connectivity for home range and movements of the rainforest arboreal ringtail possum (Hemibelideus lemuroides). *Wildlife Research,* 34**,** 177-184.

Supplementary Material - List of species recorded at the study sites and their TSWBC rating

Genus	Common Name	TSWBC Rating
Acanthiza	Brown thornbill	Indicator
Cacomantis	Fan-tailed cuckoo	Indicator
Caligavis	Yellow-faced honeyeater	Indicator
Chrysococcyx	Shining bronze-cuckoo	Indicator
Chrysococcyx	Horsfield's bronze cuckoo	Indicator
Climacteris	White-throated treecreeper	Indicator
Colluricincla	Grey shrike-thrush	Indicator
Daphoenositta	Varied sitella	Indicator
Dicaeum	Mistletoebird	Indicator
Eopsaltria	Eastern yellow robin	Indicator
Myiagra	Leaden flycatcher	Indicator
Myzomela	Scarlet honeyeater	Indicator
Neochima	Red-browed finch	Indicator
Oriolus	Olive-backed oriole	Indicator
Pachycephala	Rufous whistler	Indicator
Pardalotus	Spotted pardalote	Indicator
Philemon	Noisy friarbird	Indicator
Rhipidura	Grey fantail	Indicator
Sericornis	White-browed scrub wren	Indicator
Taeniopygia	Double-barred finch	Indicator
Todiramphus	Sacred kingfisher	Indicator
Acanthiza	Yellow-rumped thornbill	Degraded
Cacatua	Sulfur-crested cockatoo	Degraded
Cracticus	Australian magpie	Degraded
Cracticus	Grey butcherbird	Degraded
Grallina	Magpie-lark	Degraded
Manorina	Noisy miner	Degraded
Strepera	Pied currawong	Degraded

Genus	Common Name	TSWBC Rating
Accipiter	Brown goshawk	Associated
Coracina	Black-faced cuckoo-shrike	Associated
Cracticus	Pied butcherbird	Associated
Dacelo	Laughing kookaburra	Associated
Glossopsitta	Little lorikeet	Associated
Lichmera	Brown honeyeater	Associated
Malurus	Superb fairy-wren	Associated
Malurus	Variegated fairy-wren	Associated
Melithreptus	White-throated honeyeater	Associated
Merops	Rainbow bee-eater	Associated
Pardalotus	Striated pardalote	Associated
Rhipidura	Willie wagtail	Associated
Trichoglossus	Rainbow lorikeet	Associated
Zosterops	Silvereye	Associated
Accipiter	Collared sparrowhawk	Not associated
Alisterus	Australian king-parrot	Not associated
Cacatua	Little corella	Not associated
Cacomantis	Brush cuckoo	Not associated
Corvus	Torresian crow	Not associated
Dicrurus	Spangled drongo	Not associated
Entomyzon	Blue-faced honeyeater	Not associated
Gallirallus	Buff-banded rail	Not associated
Geopelia	Bar-shouldered dove	Not associated
Gerygone	Mangrove gerygone	Not associated
Hirundo	Welcome swallow	Not associated
Lalage	Varied triller	Not associated
Meliphaga	Lewin's honeyeater	Not associated
Ocyphaps	Crested pigeon	Not associated
Psophodes	Eastern whipbird	Not associated
Rhipidura	Rufous fantail	Not associated
Sericornis	Large-billed scrub wren	Not associated
Sphecotheres	Australasian figbird	Not associated
Spilopelia	Spotted dove	Not associated
Sturnus	Indian myna	Not associated
Symposiarchus	Spectacled monarch	Not associated
Todiramphus	Torresian kingfisher	Not associated
Trichoglossus	Scaly-breasted lorikeet	Not associated