Transport for New South Wales

Using technology to reduce wildlife-vehicle collisions

Literature review and directions paper

December 2024

Public

Cover photo: Koala on road, by Rodney van der Ree, WSP.

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We recognise Aboriginal and Torres Strait Islander Peoples as the first scientists and engineers and pay our respects to Elders past and present.

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Using technology to reduce wildlife-vehicle collisions

Literature review and directions paper

Transport for New South Wales

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Rev	Date	Details
A	21/08/2024	First draft for TfNSW review
B	09/09/2024	Revised draft
C	11/09/2024	Revised draft
D	18/12/2024	Final

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Glossary and abbreviations

ADS	Animal detection system
ADDWS	Animal detection and driver warning systems
AI	Artificial intelligence
ANCAAP	Australasian New Car Assessment Program
ANET	Australasian Network for Ecology and Transportation
C-ITS	Cooperative Intelligent Transport Systems
GPS	Global positioning system
LiDAR	Light detection and ranging
PIR	Passive infrared
RADS	Roadside animal detection system
ROW	Right of way
TfNSW	Transport for New South Wales
Vehicle	A generic term to encompass cars, trucks, trains
VF	Virtual fence
WVC	Wildlife-vehicle collision

Acknowledgements

This literature review and direction paper benefited from the input and experience of a wide range of people who presented and participated in the 'Using technology to reduce wildlife-vehicle collisions' symposium held in Sydney and online on the 21st May 2024. (Symposium | Using technology to reduce wildlife-vehicle collisions - Environment Institute of Australia and New Zealand (eianz.org).

We thank the following people who presented their research and experience at the symposium and/or participated in a focused workshop on the 22nd May 2024 and whose many ideas are reflected in this report: Graeme Coulson, Helena Bender, Ben Allen, Jun Zhou, Brendan Taylor, Cath Dexter, Rob Appleby, Douglas Kerlin, Ricky Spencer, Kris Le Mottee, Brenton Hayes, Julie Ravallion, Diedre De Villiers, Cassandra Thompson, Martin Meraner, Colleen St Clair, Jonathon Backs, and Liwan Liyanage.

We thank the local councils who responded to our requests for information about the virtual fence installations in their area.

We thank Julie Ravallion and Kris Le Mottee from Transport for NSW for engaging WSP Australia to be involved in this work and for their guidance and insights into the topic.

Executive summary

This literature review and directions paper has been prepared for Transport for New South Wales (TfNSW) to summarise research about technological solutions for preventing wildlife-vehicle collisions (WVC) and will be considered when the NSW Government proceed to making investment, refinement, and implementation decisions relating to WVC solutions.

The challenge

In Australia, an estimated 4 million marsupials and 6 million birds are involved in wildlife-vehicle-collisions (WVC) each year, although this number is likely higher because of undetected and unreported collisions. The impact of WVC on the safety of road and rail users is significant, and the consequences for people and wildlife alike are substantial.

The scale of economic and social impacts attributable to WVC, including vehicle damage, human death and injury, train delays and costs associated with the care of injured and orphaned wildlife, has led the NSW Government to seek direction on effective alternatives to the current reliance on fences to keep wildlife off roads and railways.

Fences, although effective at preventing many species from entering road and rail corridors, are not feasible in all locations. Recently, environmental organisations and local councils have become enthusiastic about virtual fences, although research shows virtual fences do not achieve significant reductions in WVC and therefore the need for a workable solution remains (Section 5.2.1.1).

Historically, efforts to mitigate WVC have focused on modifying wildlife movement or behaviour and the use of signs to warn motorists of the general risk of WVC. This directions paper poses the following questions:

- Do effective solutions target wildlife movement or behaviour change, driver behaviour change, or a combination of both?
- What are proven technological solutions to reduce WVC?
- What are the new and emerging technologies to reduce WVC?

The technological solutions

WVC solutions fall into three broad categories, including physical structures, solutions that involve signals only, and solutions that involve signals combined with wildlife detection systems. Within these three categories, solutions can be further distinguished according to whether they work by modifying the movement or behaviour of wildlife or whether they aim to change the behaviour or speed of vehicles and vehicle operators.

Emerging technological solutions to WVC solutions use signals as an alternative to physical barriers and wildlife crossing structures. Signals are typically sent from a device to either the wildlife or the vehicle operator. Wildlife may receive signals in the form of light, noise, scent, and/or electric shocks to deter them from entering the path of oncoming vehicles. Vehicle operators may receive signals in the form of text, lights, pictures and/or noise as warning of a potential and imminent WVC.

The success of technological solutions varies according to several factors, especially the environmental context and the wildlife being targeted. The use of signals can have significant advantages over physical approaches, including lower costs to build and maintain, reduced habitat destruction, reduced barrier effects and connectivity impacts, and more adaptability to apply it in different situations and contexts.

To understand the range of solutions available, the following schema to categorise the WVC solutions has been developed for this directions paper.

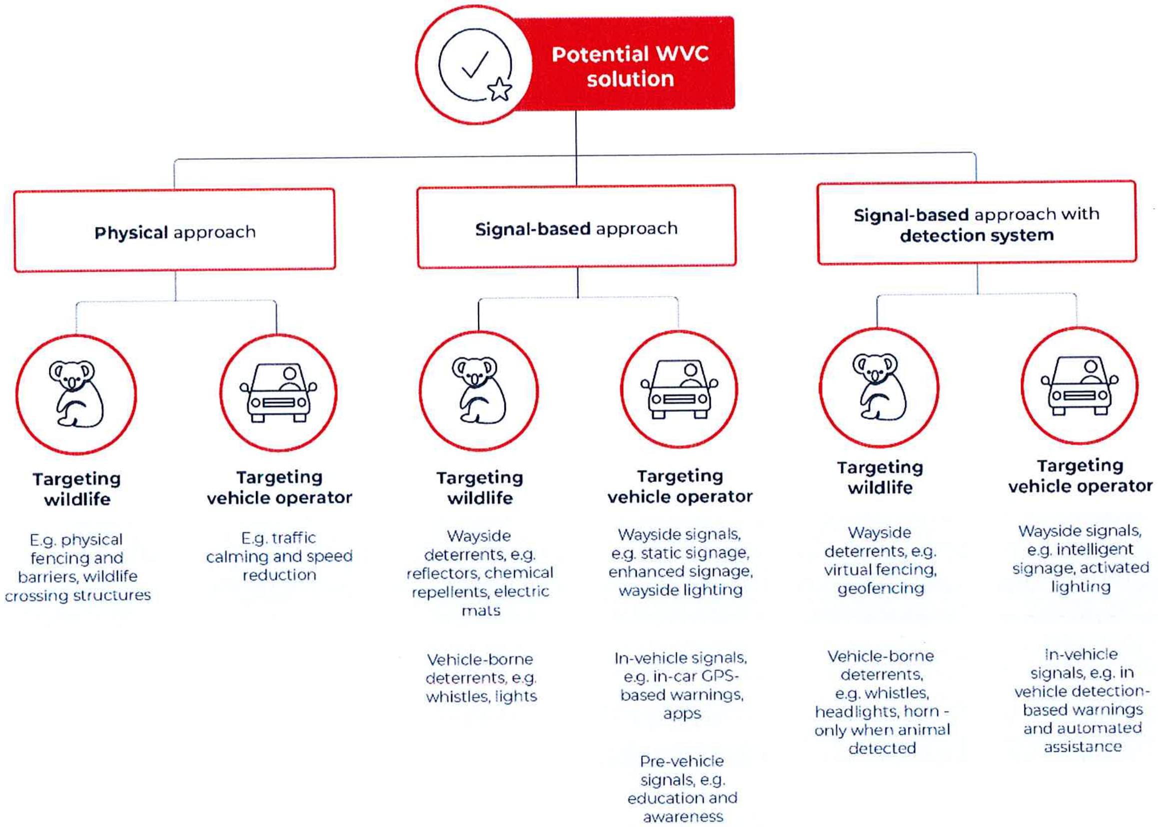

Figure ES.1 Schema to classify different types of solutions to reduce the rate and severity of wildlife-vehicle collisions.

For signalling approaches to work as intended, ecological principles need to be considered (Section 2.3.1). Signalling theory calls for the biology and behaviour of the receiver of the signal to be considered when determining the type of signals that will be most effective. Signalling solutions must be designed to ensure the signal is sent, successfully detected and then provokes the intended movement or behaviour change. Any new WVC technology that uses signalling will not be effective, no matter how well the technology sends the signal, if the signals are not effective at reaching the receiver and producing the desired response. Therefore, the first step in designing or evaluating a new WVC technology solution is to determine the correct signal.

Signals are the new frontier for reducing WVC. Technological innovation and a future-focus has generated the development of alternatives to physical barriers. The sector is shifting research and development efforts towards nuanced and increasingly refined signal solutions. Section 4 of this document includes an evaluation of signal-based approaches looking at approaches that target wildlife, including wayside deterrents and vehicle-borne deterrents, and approaches that target vehicle operators, including wayside signals, in-vehicle signals and pre-vehicle signals. Section 5 of this document includes an evaluation of signal-based approaches with detection systems looking at animal detection technology, including RADAR, LiDAR, break-the-beam sensors, Passive Infrared (PIR) motion sensors, animal-borne tags, cameras (optical, thermal, AI-assisted), acoustic sensors, seismic sensors, AI and machine learning to analyse the data collected, approaches targeting wildlife, including wayside deterrents and vehicle-borne detection-based deterrents, and approaches targeting vehicle operators, including wayside signals and in-vehicle signals. Section 6 of this document includes an evaluation of approaches that feature a combination of technologies.

The future of technology use to reduce WVC

To fully appreciate the potential of technology as an alternative to physical solutions, such as fences and wildlife crossing structures, decision makers need to contemplate possible and probable future technological advancements and refinements. The potential for vehicles to have enhanced detection and sensor features is likely in the future, in addition to future opportunities for dynamic intelligent signage that can show specific, real-time messages to drivers based on sophisticated detection technologies. For example, signage could show 'Kangaroos in the area. Drive with caution' and then 'Kangaroo on the road. Hazard ahead, slow down'.

There is immense potential for technological solutions to reduce the rate and severity of WVC. Further development and testing of technological solutions should be a high priority. To advance technological solutions, Transport for NSW should collaborate widely with other transport agencies, AustRoads, ANET and academic and industry researchers and developers in Australia and internationally to ensure the technology is effective and can be applied and implemented across jurisdictional boundaries.

It is critical to acknowledge that just as physical fences and wildlife crossing structures are not feasible or appropriate at every location, it is unlikely that technological solutions will be a comprehensive solution to all WVC. Physical solutions should complement any future development of technological solutions and limits to the effectiveness of both physical and technological solutions should be acknowledged.

1 Introduction

1.1 Background

Wildlife-vehicle collisions (WVC) are one of the most significant impacts of roads and railways globally (van der Ree et al. 2015c). Estimates of the rate of mortality are staggering – more than 350 million vertebrates are estimated to be killed annually in the USA (Forman and Alexander 1998) and more recent estimates suggest 194 million birds and 29 million mammals are killed across Europe each year (Grilo et al. 2020). Within Australia, an estimated four million marsupials and six million birds, plus other fauna groups, are killed annually (Englefield 2020). Importantly, these rates are likely to significantly underestimate the actual rates of WVC as many collisions go undetected and unreported (Grilo et al. 2020). In addition, the rates of WVC are increasing globally and in Australia along with rises in the number of vehicles on the roads, increasing road length and vehicle speeds (van der Ree et al. 2015b).

The impacts and cost of collisions between wildlife and vehicles – encompassing cars, trucks and trains – are significant and far-reaching. From an animal welfare perspective, the injury and potentially slow death of large numbers of animals each year is significant and something much of the community fails to acknowledge (Lunney 2013). From a conservation perspective, mortality of threatened species due to WVC can be a major contributor to species decline (Grilo et al. 2021). The economic costs are also considerable and encompass vehicle repairs (Huijser et al. 2009), human death and injury, and train delays (Dorsey et al. 2015), as well as costs to collect and hand-rear injured and orphaned animals (Englefield et al. 2018). Socially, the injury and death of humans from WVC are significant and also likely under reported.

The standard approach to reducing and preventing WVC is fencing to keep animals off the road or railway and the installation of crossing structures, such as underpasses and overpasses, that enables fauna to safely cross the transport infrastructure (Smith et al. 2015, van der Ree et al. 2015a). A comprehensive international literature review and meta-analysis clearly demonstrated that for many species of wildlife, these methods are effective at reducing rates of WVC, albeit with room for improvement (Rytwinski et al. 2016). Unfortunately, it is not feasible to implement these mitigation measures everywhere for a diversity of reasons, including site constraints (e.g. flooding destroys fences, the presence of rare vegetation types, topography), high costs for installation and maintenance, and because many species are able to climb or fly over fences.

Technological solutions to WVC – broadly defined as systems that detect wildlife and/or alert the driver or the animal – have been implemented with limited success alongside fences and crossing structures since at least the 1970's (Olbrich 1984, Schafer and Penland 1985, Schafer et al. 1985, Huijser et al. 2015). The research and development of technological solutions has progressed rapidly in more recent years, aided by technological and computational advances across society, including object detection systems, artificial intelligence (AI) and machine learning (Bengio 2016). There has been an increased focus and desire to apply these new technologies to reduce the rate and severity of WVC in Australia and abroad.

Technological solutions can focus on modifying the response of wildlife and/or the response or behaviour of vehicle operators and/or vehicles. Technological solutions that aim to modify driver or vehicle responses range from simple road signs to complicated systems that detect wildlife on the road or railway and automatically trigger a response from an automated vehicle. Animal deterrent systems can include acoustic devices attached to the vehicle that operate whenever the vehicle is in motion to other systems that only operate when a vehicle approaches and when wildlife are present.

A comprehensive understanding of the effectiveness of the various technological solutions is critical to ensure it is fit for purpose and is applied with a thorough knowledge of any limitations. Importantly, the degree of effectiveness is important, including consideration of:

— Which species of wildlife is the technology applicable to?

— What amount or percentage is the rate or severity of WVC reduced?

- Under what road (e.g. highway, country road) or rail (commuter, freight, high-speed) conditions; landscape e.g. rural, bushland, suburban), weather conditions (day, night, rain, snow etc) and traffic conditions (e.g. speed, volume, type) is the technology effective?
- Is there any habituation by wildlife to the deterrents or by vehicle operators to the warnings being used?

1.2 Aims and objectives

This literature review and directions paper aims to evaluate the current and emerging technological solutions with potential to reduce WVC globally and with a focus on the Australian context, in order to advise Transport for New South Wales (TfNSW) on the best opportunities for investment, refinement and implementation of solutions to achieve their objectives on NSW roads and railways. The relevant objectives for TfNSW, in order of priority are to:

- Improve driver safety, particularly reducing human fatalities and injuries on road and rail.
- Reduce mortality and injury of wildlife from WVC.
- Reduce road and rail impacts to wildlife connectivity.

TfNSW will use the results of this review and synthesis to guide the implementation of a 2023 election commitment to develop, test and trial the most promising technological solutions to reduce the rate and severity of WVC on roads and railways across NSW.

2 Methods

2.1 Information and data sources

The information used in this review and synthesis was gathered from a comprehensive literature search as well as through a symposium and workshop with leading experts from Australia and around the world.

The literature review was undertaken by searching relevant academic databases for terms relating to roadkill, wildlife-vehicle collision, mitigation and technology. All papers identified in this search were reviewed, and the references in these publications were further reviewed in an effort to collate as many relevant references as possible. The literature included peer-reviewed scientific publications and the grey literature, including theses, government and industry reports and product information from component manufacturers.

A symposium entitled 'Using technology to reduce wildlife-vehicle collisions' was held in Sydney and online on the 21st May 2024 (Symposium | Using technology to reduce wildlife-vehicle collisions - Environment Institute of Australia and New Zealand (eianz.org)). Almost 300 people from a wide range of organisations and community groups registered to attend the symposium, reflecting the importance of the topic to many in the community.

The symposium included:

- A summary of the rates and impacts of WVC globally.
- A description of the range of technological approaches to reduce WVC.
- An explanation of animal behaviour and biology relevant to developing animal deterrents and warning devices.
- Technological solutions applied in wildlife management that could be applied to solve the WVC challenge.
- The results of field trials in Victoria and Queensland to test and measure the effectiveness of different technological solutions.
- Case studies of attempts to develop or implement different methods, including systems to detect turtles on roads, AI sensors to prevent elephant-train collisions in Bangladesh, deterrents to reduce bear-train collisions in Canda and ungulate-train collisions in Sweden
- An overview of the systems and testing facilities used in Australia to test and rate vehicle safety features.

A one-day workshop was held on the 22nd May 2024 with many of the local and international experts who participated in the symposium (see Acknowledgements for those involved) to prepare a peer-reviewed publication on the outcomes of the symposium. Many of the ideas and discussions arising during the workshop have been incorporated into this review and synthesis.

2.2 Schema to categorise WVC solutions

There is a wide range of technological solutions that aim to reduce the rate of WVC in Australia and internationally which can be categorised or organised in a myriad of different ways. The schema adopted for this review (Figure 2.1) is based on two-levels of categorisation. The first level or tier in the schema separates potential solutions based on whether they primarily involve the use of (i) physical structures, (ii) signals only or (iii) signals with animal detection systems. The second level or tier separates solutions based on whether they aim to change the behaviour or movement of wildlife or whether they target vehicle operators (or vehicles) and aim to change their behaviour or speed.

The potential solutions in each category are not ordered to reflect when the technology was developed, the degree of technological complexity or effectiveness. It was not possible to order these solutions because the degree of effectiveness of the exact same solution can vary depending on the species of wildlife, changes to road or traffic conditions and other environmental conditions. Similarly, a minor modification in one aspect of a solution may change effectiveness and thus the order will likely vary over time.

Future potential solutions are also expected fit within the schema outlined in Figure 2.1.

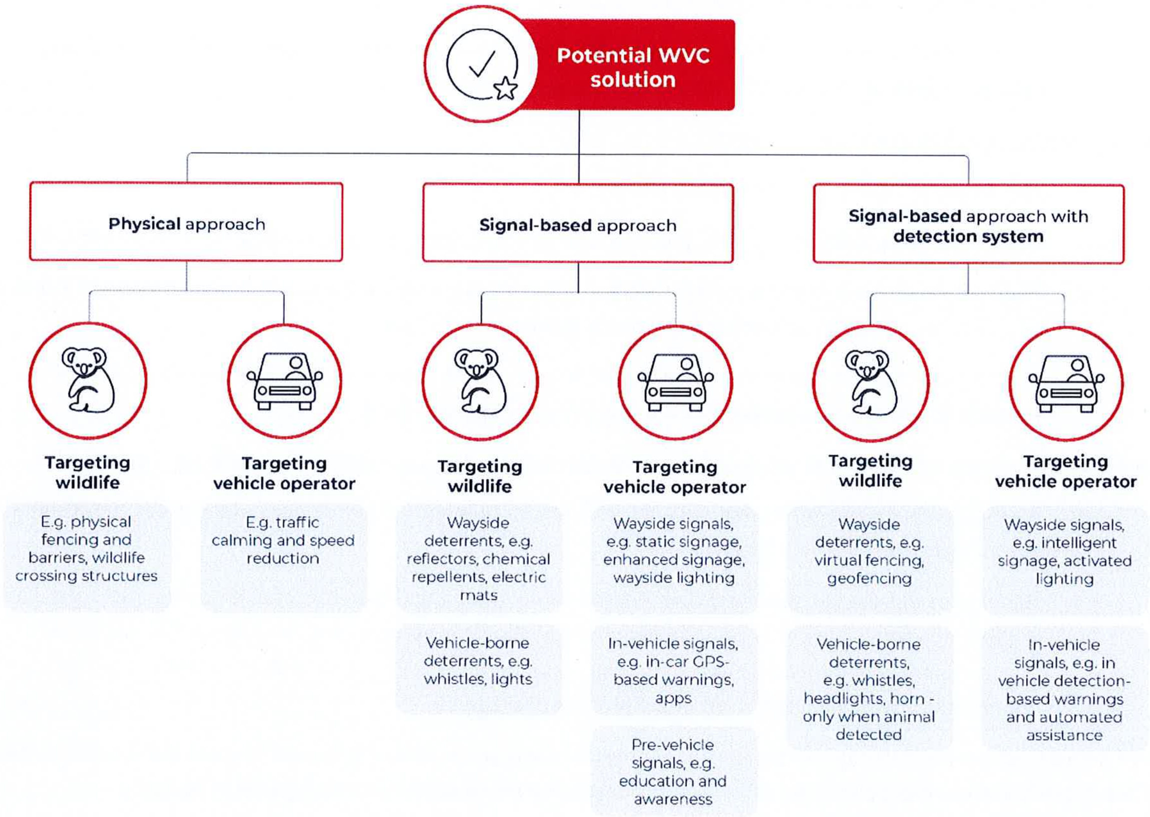

Figure 2.1 Schema to categorise the suite of physical and technological solutions to solve wildlife-vehicle collisions.

2.3 Approaches to evaluate technological solutions

Three approaches guided the evaluation of each potential solution and informed future research and development opportunities:

- Signalling theory (Section 2.3.1)
- An iterative process for research, development and testing (Section 2.3.2)
- Scientifically robust methods for future trials (Section 2.3.3)

2.3.1 Signalling theory

A fundamental aspect of emerging WVC solutions is the use of signals as an alternative to physical barriers (e.g. fencing) and wildlife crossing structures. Signalling in the context of reducing the rate and severity of WVC is any action, image, movement, sound, electrical impulse or radio wave that conveys information to an animal, driver, vehicle or other device that is intended to modify the behaviour of vehicle operators or wildlife, reduce vehicle speed and thereby reduce the likelihood of a WVC.

In all signal systems that aim to reduce WVC, there is a sender of the signal(s), a receiver who receives the signal(s), and an expected or intended response from the wildlife, vehicle operator or vehicle (Figure 2.2 to Figure 2.5).

For most current potential WVC solutions, the sender and receiver can fit into the following categories:

- <u>Wildlife receives the signal:</u>
  - The sender is usually a human-made device.
  - The signal is typically noise, light, scent and/or or electric shock, intended as a warning or deterrent.
  - Wildlife are the intended receiver of the signal.
  - The intended response is for the targeted wildlife to move away from the device and thus the road, railway or vehicle, and thereby reduce the likelihood of a WVC.
- <u>Vehicle-operator or vehicle receives the signal:</u>
  - The sender is usually a human-made device.
  - The signal is typically text, lights, pictures, and/or noise, intended as a warning to vehicle operators.
  - The vehicle operator is the intended receiver of the signal, which can include human drivers of vehicles as well as an in-vehicle automated system or autonomous vehicle.
  - The intended response is avoidance of wildlife on the road, mostly achieved through vigilance and slowing down, or a less-severe WVC due to reduced vehicle speed.
- <u>Wildlife or vehicle-operator receives the signal, with an intermediate device that detects wildlife and/or vehicles:</u>
  - As for the above categories, but with the addition of an intermediary device, which processes a signal before it reaches the end-receiver.
  - Benefits of this category include finer control of the timing and type of signal. For example, roadside wildlife deterrents may only be activated when a vehicle is approaching, intelligent road signs only inform vehicle operators when an animal has actually been detected, as well as potential monitoring opportunities from data collected in the processing stage.

The use of signals can have significant advantages over physical approaches, including lower costs to build and maintain, reduced habitat destruction, reduced barrier effects and connectivity impacts, and more adaptability to apply it in different situations and contexts.

For signalling approaches to work as intended, it is important to consider the biological principles of signalling at an early stage in the development of potential technological solutions. This theory involves considering the biology and behaviour of both the sender and receiver of the signal, and the type of signals that will be most effective in communicating between them. A thorough understanding of the type of signal and its impact prior to designing and implementing a modified or new WVC solution is important to maximise the likelihood the system works as intended and minimises the chances of unintended negative consequences.

The challenges of signalling technologies include determining appropriate signal types that can be sent and subsequently detected by the target and produce the intended response, as well as developing detectors and processing technology for intermediary devices that produce accurate results.

Any WVC technology that uses signalling will not be effective, no matter how well the technology sends the signal, if the signals are not effective at reaching the receiver and producing the desired response. Therefore, the first step in designing or evaluating a WVC technology solution is to consider and evaluate signal, including:

1. Is the signal in the detection range of the target? e.g. can the target species hear, see, or feel this signal?
2. Is the signal the appropriate strength for the target considering other distractions on the road or railway? e.g. is the sound loud enough and within the hearing frequency range of the target species? Is the species capable of detecting the lighting?
3. Does the signal elicit the intended response from the receiver? e.g. does the animal move away from the road or railway? To what extent does the vehicle operator increase vigilance and/or slow down?

The first two elements can be determined through an understanding of the species biology, such as determining the sight and hearing capabilities of the target species. The third element requires an understanding of the target species behaviour and this may require targeted research. For example, Lee et al. (2010) found that kangaroos move in unpredictable directions along erratic paths in response to high level threats and adopt stationary vigilant behaviour in response to low level threats. Erratic responses were more likely at night, in areas with less vegetation cover, in smaller groups of animals, and for certain species of macropods. This information can help system developers consider how the target species might respond to potential stimuli used in deterrent systems.

An example of a study that considered this principle as an initial step is research by Seiler et al., (unpub. data) who tested which acoustic signals played through a speaker in the forest elicited a flight response in wild deer in Sweden. They found that a human voice was more effective at eliciting the intended response in the wildlife than the alarm signals often used in roadside deterrent systems. It was hypothesised that this response to the human voice may have been due to hunting pressures from humans, and therefore the human voice may be less effective in species that are not subject to hunting. This example demonstrates the importance of testing and determining signal appropriateness in each context before the design and field trialling stages of a technological solution.

Unintended consequences of signals should also be considered. For example, will the signal cause unacceptable disturbance to the surrounding environment, and what flow on effects could this have? Will the target species become habituated to the signal over time, causing it to lose its effect? Could the signal be an attractant to other species? These questions should be explored through initial signalling studies.

Because it is crucial to thoroughly consider signalling principles before any other stages proceed so that time and money are not wasted and ecosystems are not damaged by unintended impacts, this principle is the first stage of development and evaluation framework (Section 2.4, Figure 2.7) used to evaluate WVC solutions in this review.

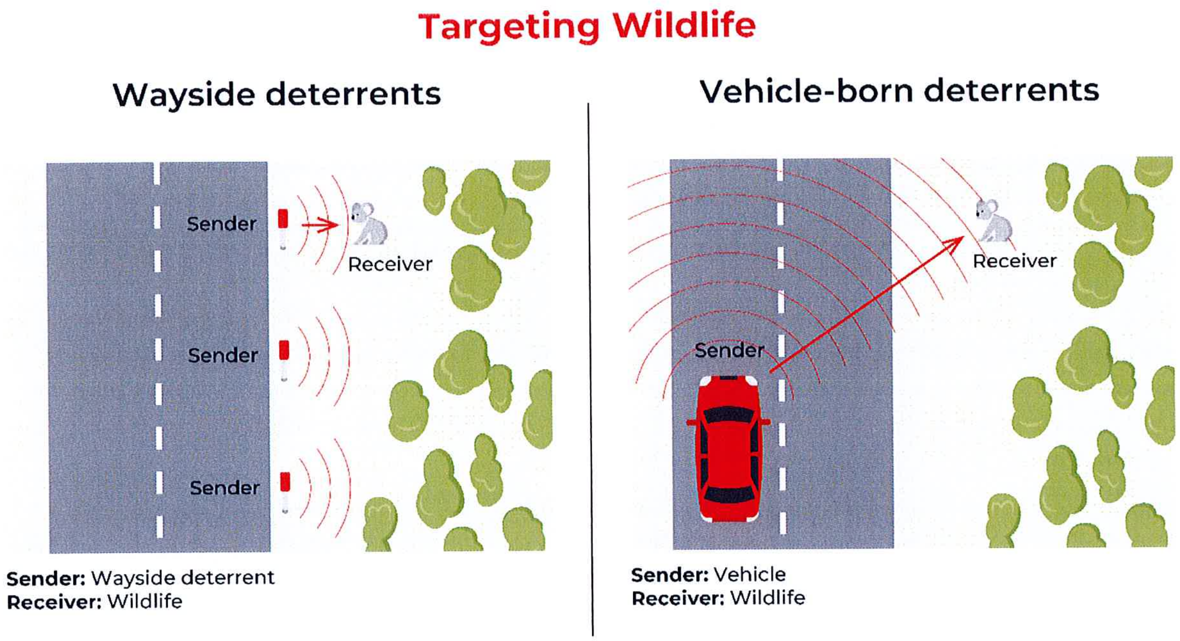

Figure 2.2 Example of signals emitted to warn and deter wildlife from devices installed on the verge of roads and railways (left) and being emitted from vehicles (right).

Figure 2.3 Example of signals to warn vehicle operators of the increased risk of WVC emitted from devices installed on the verge of roads and railways (left) and within vehicles (right).

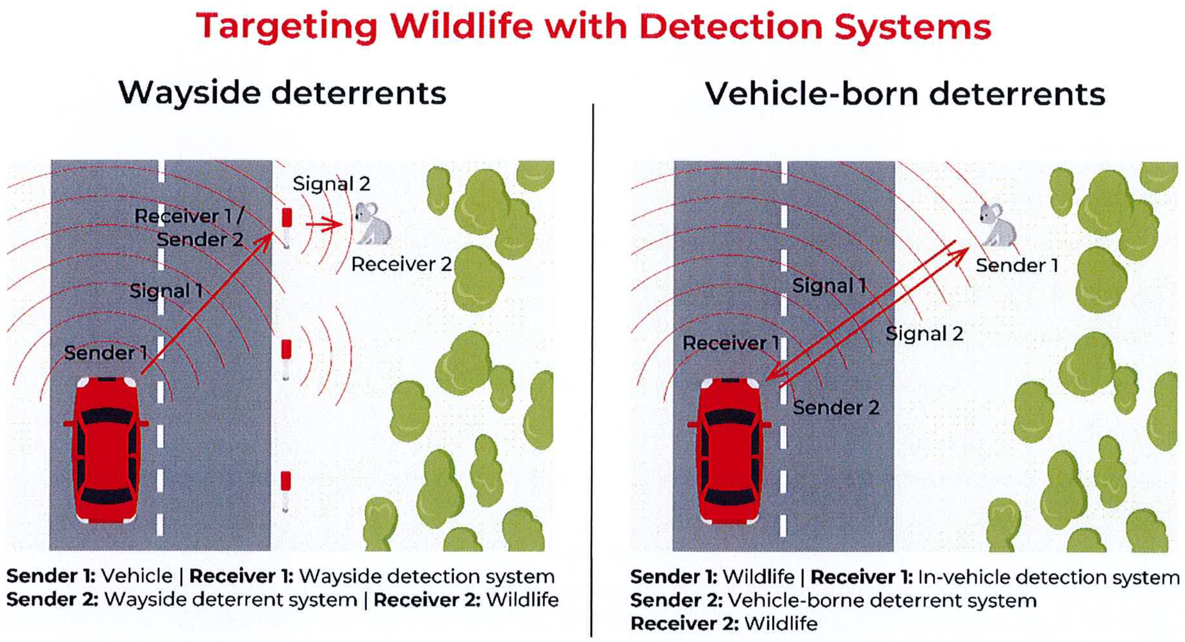

Figure 2.4 Example of signals to warn and deter wildlife that are emitted from vehicles to devices installed on the verge of roads and railways (left) and signals being emitted from vehicles after wildlife are detected by the in-vehicle detection system (right).

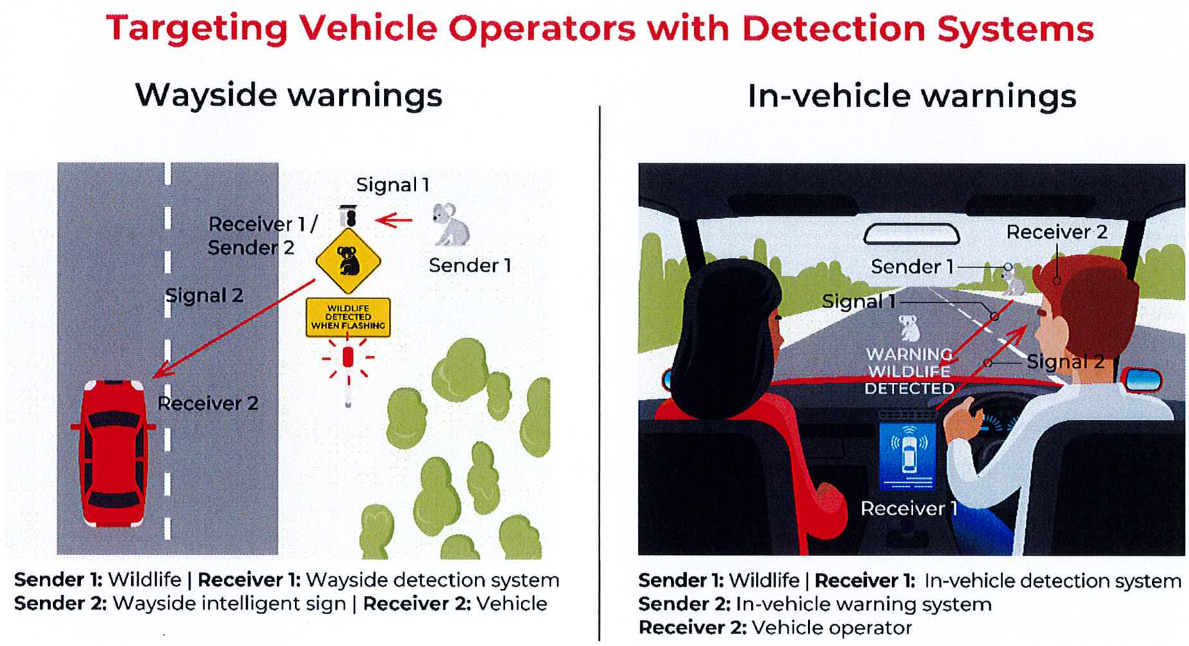

Figure 2.5 Example of signals to warn motorists of the presence of wildlife – where wildlife are detected by wayside detection systems which activates intelligent signs (left) or in-vehicle detection systems that activate in-vehicle warnings systems (right).

2.3.2 *An iterative process for research, development and testing*

The development and refinement of new technological solutions is an iterative process with multiple feedback loops that progresses through:

- Identifying a problem.
- Developing a concept solution, often with preliminary investigations to support concept designs.
- Concept and detailed design and building of prototypes.
- Testing the prototype and refining the design.
- Testing a refined solution in the field, with subsequent updates and further refinements.
- Eventually (hopefully) developing a solution with a known level of effectiveness.

A key step through each design stage is the rigorous testing of the technology to ensure it operates and functions as intended (Section 2.3.3).

This approach is reflected in the Technology Readiness Level index (TRL) (Figure 2.6) which is a globally recognised and adopted framework to assess and benchmark the progress of technological solutions from early or basic research through to the implementation of a system that functions over the full range of expected conditions. The index has nine levels that describe the maturity of a technology and was originally developed by NASA in the 1970s and has since been adopted around the world and in various disciplines (Table 2.1).

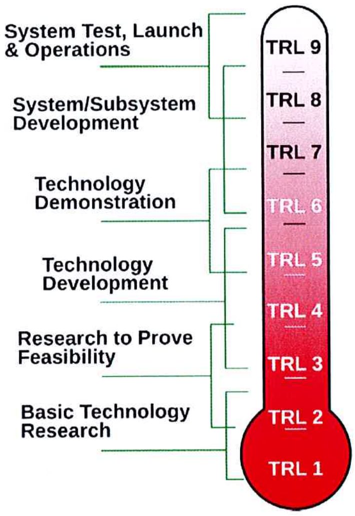

Figure 2.6. The Technology Readiness Level index. Source: By Hari Seldon - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=148410150

Table 2.1. Description of each Technology Readiness Level adopted by the Horizon 2020 works program of the European Union (European Commission 2014)

TRL	Summary
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in a laboratory
5	Technology validated in relevant environment
6	Technology demonstrated in relevant environment
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

The TRL index implies a linear approach to developing effective technological solutions, but in reality, there are many iterative steps and feedback loops required to progress to the next level. Adopting an iterative approach and documenting the degree of success or effectiveness at each stage maximises the likelihood that an overall successful solution can be found, as well as the ability to subsequently combine different components to develop more effective combined solutions. This approach also enables existing systems to be updated into the future as specific components are enhanced. For example, an intelligent sign (Section 5.3.1.1) alerting drivers to the presence of kangaroos could be enhanced in the future as animal detection and identification systems (Section 5.1) are improved.

This iterative approach is also applied to the development and evaluation framework (Figure 2.7) and which guided the evaluation of the current solutions in this review and directions paper.

2.3.3 Scientifically robust methods for trials

Robust trials at each iterative step in the process, from concept through to in-situ tests in the operational environment (i.e. TRL 1 through to TRL 9) are crucial to developing a system and evaluating the efficacy of a WVC solution within its real-world context (Van der Grift et al. 2013, Van der Grift et al. 2015). A poorly designed field trial may yield misleading results, provide limited useful feedback, and be inadmissible as evidence for a specific solution. There are many examples of WVC solutions that have undergone sub-par field trialling, resulting in a lack of accurate information despite investment of significant resources (Rytwinski et al. 2015, Soanes et al. 2024).

Existing solutions should also continue to be trialled to identify and address any uncertainties in effectiveness and when they are applied in new or novel contexts. It is important for new solutions not to rush to field trialling before they gather confidence in the appropriateness of the solution for the biology and behaviour of the species and the functioning of the technology; therefore, this principle is the last stage in the development and evaluation framework(Figure 2.7), Section 2.4). Guidelines to undertake scientifically robust field trials have been detailed elsewhere (Van der Grift et al. 2013, Rytwinski et al. 2015, Van der Grift et al. 2015, TMR 2024a) and should address the following:

- Define success.
- Define the target species and the infrastructure, traffic and environmental conditions that the system is intended to function in.
- Use a replicated before-after-control-impact study design.
- Explore unintended impacts of the different solutions or individual components.

- Include complete and transparent descriptions of the technology and assessment methods to enable independent testing, auditing and verification of results.

2.4 Development and evaluation framework

The development and evaluation framework (Figure 2.7) was used to assess the current and emerging technological WVC solutions while considering the principles of signalling theory (Section 2.3.1), the iterative process for research, development and testing (Section 2.3.2) and principles for robust trials design (Section 2.3.3). The framework (Figure 2.7) is designed to identify areas where information is missing, or improvement is needed for each type of WVC solution.

The framework is a qualitative assessment of the potential solution at reducing rates of WVC and identifies areas for further research and development. The framework can be used by end-users to assess types of systems broadly or it can be used to assess specific systems proposed for certain species and/or local contexts.

This framework can also be used by developers of technological solutions to test and refine their potential solutions and evaluate where the system may have failed. In this review, the framework is used to evaluate effectiveness of systems and components or stages of systems at reducing the rate and severity of WVC.

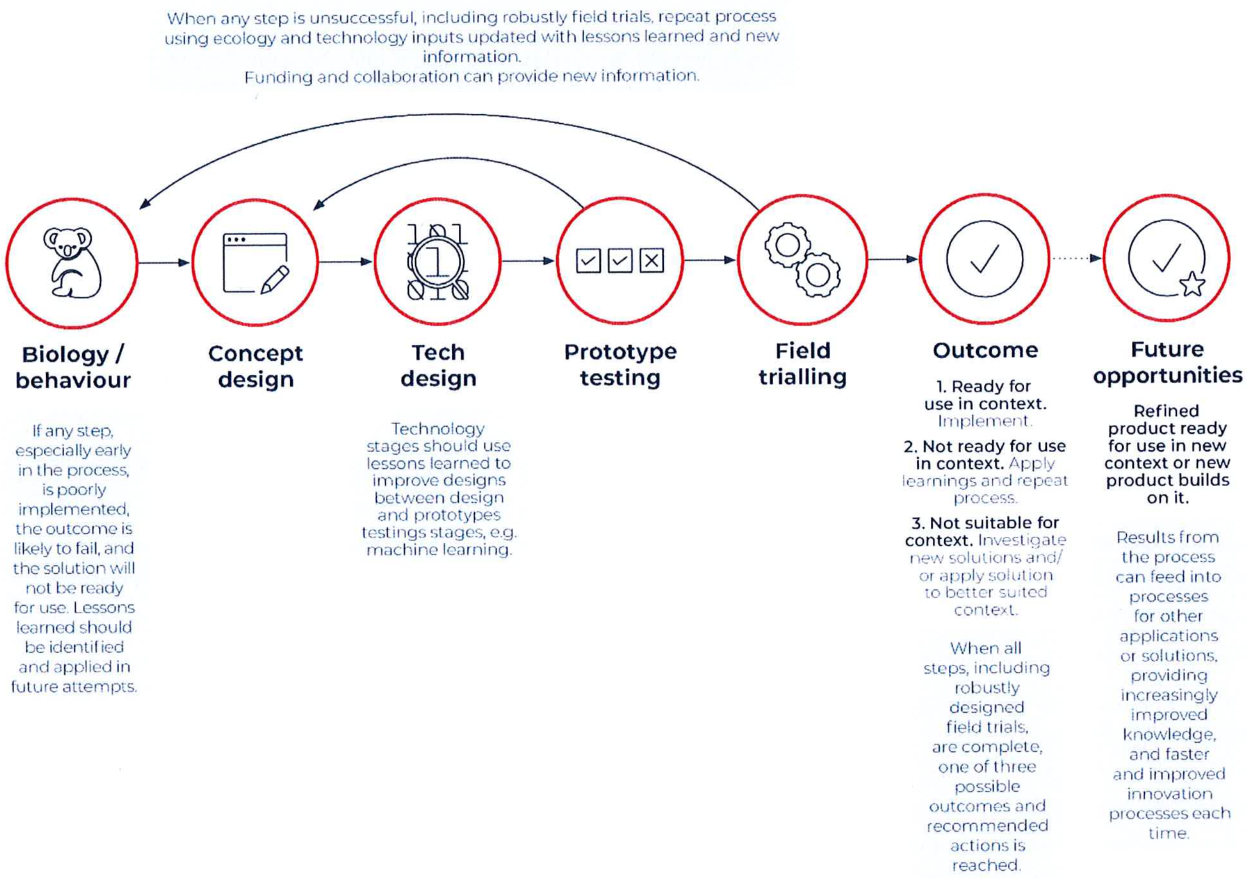

Figure 2.7 Development and evaluation framework used to evaluate the effectiveness of different technological solutions to WVC and identify which components or stages in the system require further development.

3 Evaluation of physical approaches

3.1 Targeting wildlife

3.1.1 Physical fencing and barriers

Fencing is widely used around the world to prevent animals from accessing roads and railways and to funnel them towards crossing structures or 'safer' locations to cross the road or railway 'at-grade' (van der Ree et al. 2015a). Tall mesh fences to reduce rates of WVC were first built in the 1960s to prevent large ungulates from entering highways in Europe and North America (Puglisi et al. 1974, Falk et al. 1978) and have since been further refined for ungulates and large carnivores (Ford et al. 2022) as well as a range of other species, including koalas (TMR 2024b), turtles (Aresco 2003, Reses et al. 2015), amphibians (Buck-Dobrick and Dobrik 1989, Jackson and Tyning 1989) and reptiles (Macpherson et al. 2021). Fences can be made of a range of materials (e.g. mesh, plastic or metal sheets, electric wires, noise walls, concrete Jersey barriers) and vary in height and design (e.g. with overhanging lip, buried base), depending on the target species and local context.

A meta-analysis of 99 data sets from 50 international studies (Rytwinski et al. 2016) found that fences and crossing structures can reduce rates of WVC of large mammals by 83%, and fences with or without crossing structures reduced rates of WVC by 54%. A key determinant in fence effectiveness is fence length and ongoing maintenance, as any breaks in fencing can result in fauna accessing the road and resulting in WVC (van der Ree et al. 2015a). These breaks can occur from natural damage (e.g. fallen trees), vandalism, errant vehicles or gates on access roads and tracks being left open.

While fencing can significantly reduce rates of WVC, there are many situations where fencing is not feasible or desirable. Fencing necessarily increases the barrier effect of the road or railway and either prevents all crossings or forces animals to cross the transport infrastructure at specific locations, either at wildlife crossing structures or at fence ends. In an effort to reduce construction costs and the amount of vegetation removal, short lengths of fencing, rather than continuous lengths of fencing, may be installed with crossing structures to funnel animals to the crossings (Spanowicz et al. 2020). However, there is an increasing body of evidence that short lengths of fencing has a limited effect on reducing rates of WVC and are less effective than longer lengths at funnelling animals to safe crossings (Huijser et al. 2016, Plante et al. 2019).

Fencing through natural areas may require extensive clearing of native vegetation to build and maintain the fence, resulting in extensive habitat loss. Fences through areas on the urban-rural fringe may be aesthetically unpleasing, as well as require numerous breaks for driveways and other access tracks, which may reduce effectiveness. Fencing can be expensive to build and maintain, especially for long lengths of fencing and in specific situations, such as in rocky areas, flood zones, and areas subject to drifting sand or snow. Finally, many species are able to climb (e.g. arboreal species), glide (e.g. gliders) or fly (e.g. birds and bats) over fencing and can therefore access the road or railway.

In summary, fencing is an important feature to reduce rates of WVC, but is not suitable everywhere, can be expensive to build and maintain and is not effective for all fauna.

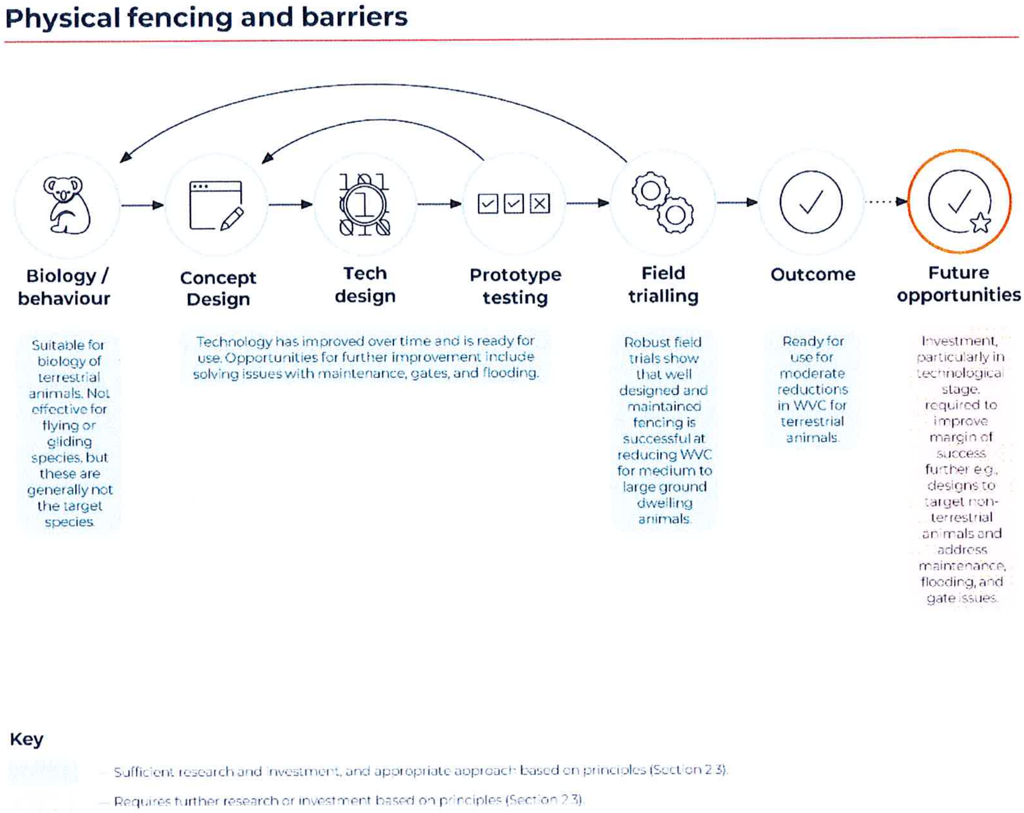

Figure 3.1 Qualitative assessment of physical fences and barriers at reducing rates of WVC and identification of areas for further research and development.

3.1.2 Wildlife crossing structures

Wildlife crossing structures are physical structures that allow the safe movement of fauna under or over a road or railway (Smith et al. 2015). The primary aim of crossing structures is to maintain fauna movement and ecological connectivity, and to prevent injury and mortality of wildlife while they are crossing. In contrast, the primary aim of fencing and other barriers is the reduction or prevention of WVC and to funnel wildlife to crossing structures.

While there are many different types of wildlife crossing structures, they are typically grouped into two main categories:

- Underpasses - includes bridges and culverts and they allow movement under the transport infrastructure.
- Overpasses - includes vegetated land bridges, tunnels, glider poles and canopy bridges and they facilitate movement above the transport infrastructure.

Wildlife movement can also be encouraged or facilitated at a-grade crossings, which are described in Section 6.1.

There is a large and growing body of evidence from Australia and globally that wildlife crossing structures are used by a wide variety of species, including amphibians, reptiles, arboreal mammals, terrestrial mammals, birds and bats (van der Ree et al. 2008, Lesbarrères and Fahrig 2012, Smith et al. 2015, Denneboom et al. 2021, Soanes et al. 2024). Wildlife crossing structures are now recommended globally as the preferred approach to maintain and enhance connectivity and movement of wildlife across roads, railways and other linear infrastructure. However, the placement and design of wildlife crossing structures has a major influence on the rates of use and their suitability for different species, with different species preferring different types of structures and/or specific designs.

A recent extensive literature review and synthesis asked "what is the evidence that wildlife crossing structures mitigate the barrier effect of roads on wildlife movement?" (Soanes et al. 2024). Ninety-eight percent of the 313 relevant studies that were reviewed showed that crossing structures allowed cross-road movement and approximately 60% of studies showed an improvement in movement. Importantly, only 14% evaluated whether crossing structures resulted in a change in animal movement after construction. The two key conclusions of this global review were that (1) wildlife crossing structures *can* mitigate the barrier effect of roads and railways, and (2) most studies and monitoring programs were unable to detect (mostly due to inadequate study designs) whether there was a change in the rate of animal movement after construction, or whether the mitigation prevented a population decline.

There are many constraints with crossing structures that limits their widespread adoption, including:

- High cost - vegetated land bridges can cost millions of dollars and are especially expensive when retrofitting to existing roads and railways.
- Different species require different designs and specific conditions. For example, amphibians may require underpasses that remain moist, while other species prefer dry underpasses.
- Road and railway designs may limit the adoption of certain structure types. Underpasses are most easily built where the road or railway is on fill or already elevated, while land bridges are most cost-effective where the transport infrastructure is at- or below-grade.
- Expensive crossing structures are often restricted to locations where adjoining land and habitat is permanently conserved to maximise the long-term benefits.
- Wildlife crossing structures on their own do not significantly reduce rates of WVC beyond the immediate area of the structure and for the specific species or group of species that it is designed for. Crossing structures typically require fences and other physical barriers (Section 3.1.1) to funnel wildlife to the crossing structure and prevent wildlife from accessing the road or railway.

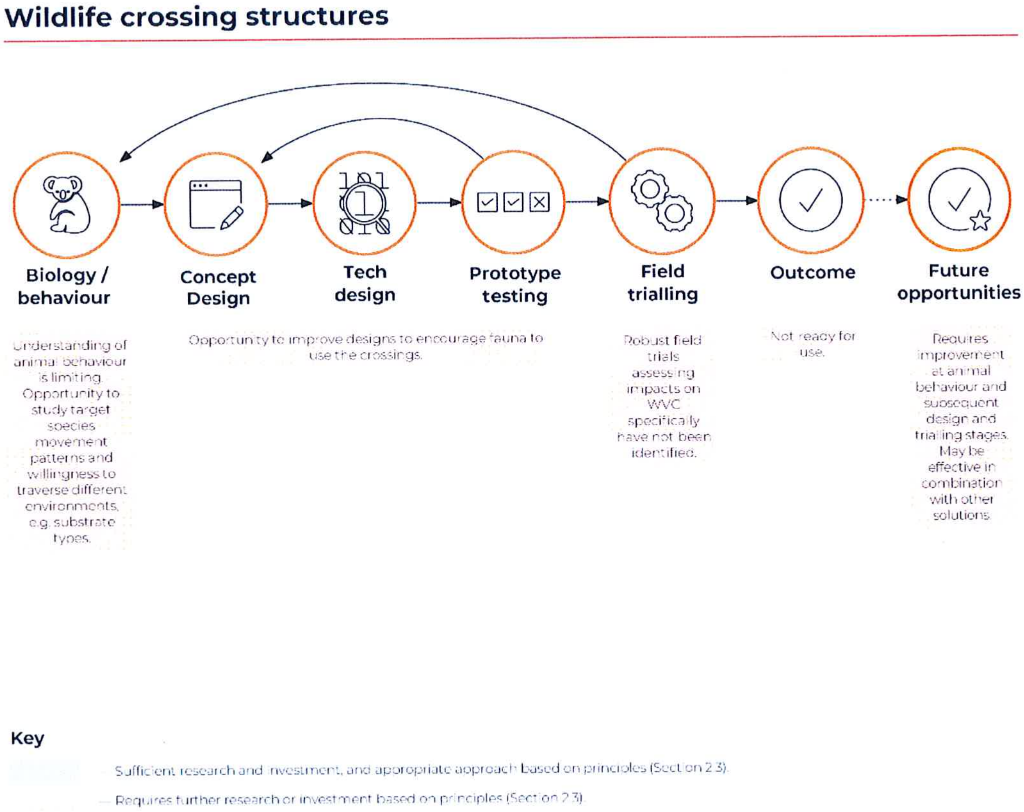

Figure 3.2 Qualitative assessment of wildlife crossing structures (in the absence of fencing) at reducing rates of WVC and identification of areas for further research and development. Note that wildlife crossing structures are effective at allowing for the safe movement of wildlife – the assessment shown here focuses primarily on the ability of crossing structures to demonstrably reduce rates of WVC.

3.2 Targeting vehicle operators

3.2.1 *Traffic calming*

The aim of traffic calming is to use physical and non-physical elements to slow down traffic and reduce traffic volumes to improve road safety for both motorists and non-motorists (Ambros et al. 2023). Traffic calming has been applied since the 1960's in Europe and Australia in the 1980s (Ambros et al. 2023) typical using speed bumps, signage, round-a-bouts, radar speed cameras, and overall traffic flow reduction through the redirection of traffic away from certain roads and onto a small number of preferred roads. A study which aimed to determine the best method to reduce traffic speed in an area concluded that a raised crosswalk and lane narrowing were the best at lowering traffic speed (Gonzalo-Orden et al. 2016). Other traffic calming measures such as radar speed cameras, normal crosswalks and pedestrian push buttons did not provoke an effective traffic calming response on their own, and required multiple traffic calming measures to be effective (Gonzalo-Orden et al. 2016). The best results to elicit a traffic calming response from drivers is when multiple traffic calming measures are used along the roadway and within short succession. This study was conducted in an urban setting, therefore results may differ in rural settings. Another traffic calming option is the use of rumble strips, which are raised elements in the road that cause a vehicle to vibrate as they drive over them. An eight-week trial in Tasmania demonstrated a 59% decrease in WVC at treatment sites using rumble strips (Lester 2015).

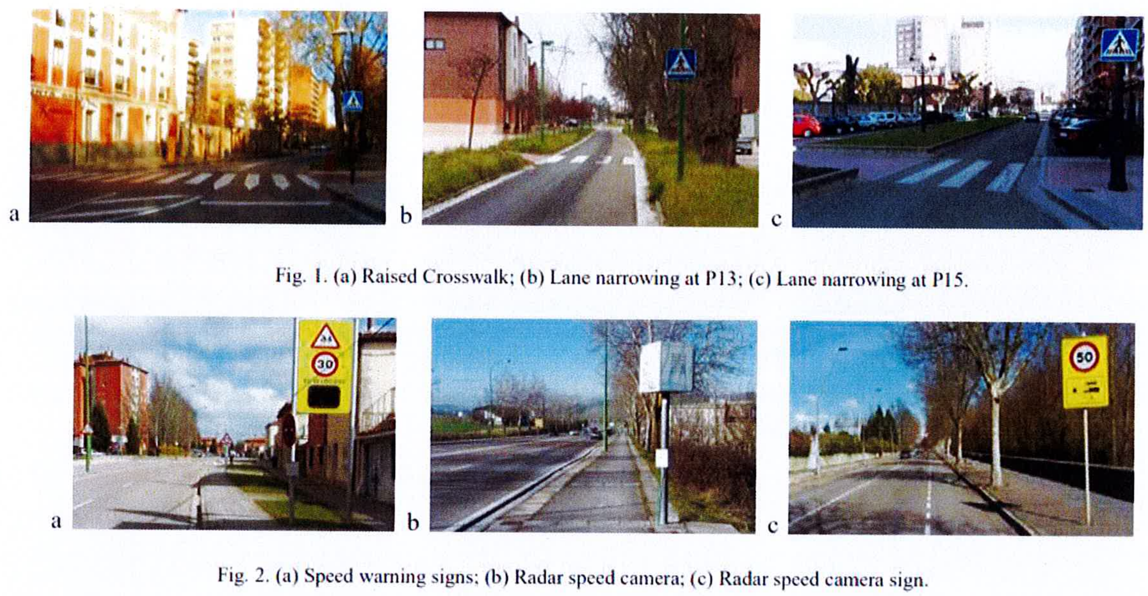

Figure 3.3 Examples of traffic calming measures in urban and suburban areas (Source: Gonzalo-Orden et al. 2016)

The effectiveness of traffic calming at reducing rates of WVC is related to various factors including the size of the traffic calmed area, the amount of habitat for wildlife and its carrying capacity (i.e. size of the wildlife population), and the surrounding human density and traffic volumes. In areas that have small habitat patches and high human density, traffic calming is considered relatively unsuccessful, unless there is a dramatic reduction in traffic volume (van Langevelde and Jaarsma 2009). Modelling studies have determined that traffic calming can reduce habitat fragmentation effects by allowing wildlife to cross minor rural roads by redirecting traffic to other roads (Jaarsma and Willems 2002). This decrease of fragmentation may reduce the rates of WVC in rural areas, but in turn increases traffic volume on a small number of major roads nearby; however, this has not been widely studied and is not fully understood.

Physical traffic calming strategies such as speed bumps and chicanes may be inappropriate in rural settings and 'greener' alternatives, where trees are retained or grown close to the road edge to give an appearance of a narrow road, can encourage motorists to drive more slowly (Jaarsma and Willems 2002). A NSW Department of Planning, Industry and Environment fact sheet on changing driver behaviour in relation to koala strikes suggested exploring rumble strips on roads with posted speed limits at or below 60km/hr, away from built up areas (Department of Planning 2020).

There are many constraints with the implementation of traffic calming to reduce rates of WVC, including:

- Traffic calming is most appropriate on roads with low volume and speed of traffic. Traffic calming is not feasible on high-volume or high-speed arterial roads or on railways.
- Many studies on the effectiveness of traffic calming generally lack scientific robustness (Ambros et al. 2023) and most studies assessing the effectiveness of traffic calming at reducing rates of WVC are based on simulation models (e.g. Jaarsma and Willems 2002, van Langevelde and Jaarsma 2009).
- The creation of potentially hazardous road conditions such as blind spots, road obstructions, rumble strips and rapidly decelerating vehicles.
- Multiple traffic calming measures are likely required to maximise effectiveness.
- The effectiveness relies on the motorist being vigilant and obeying the traffic calming requirements.
- Redirects traffic onto other roads, which may subsequently require mitigation measures to reduce rates of WVC.

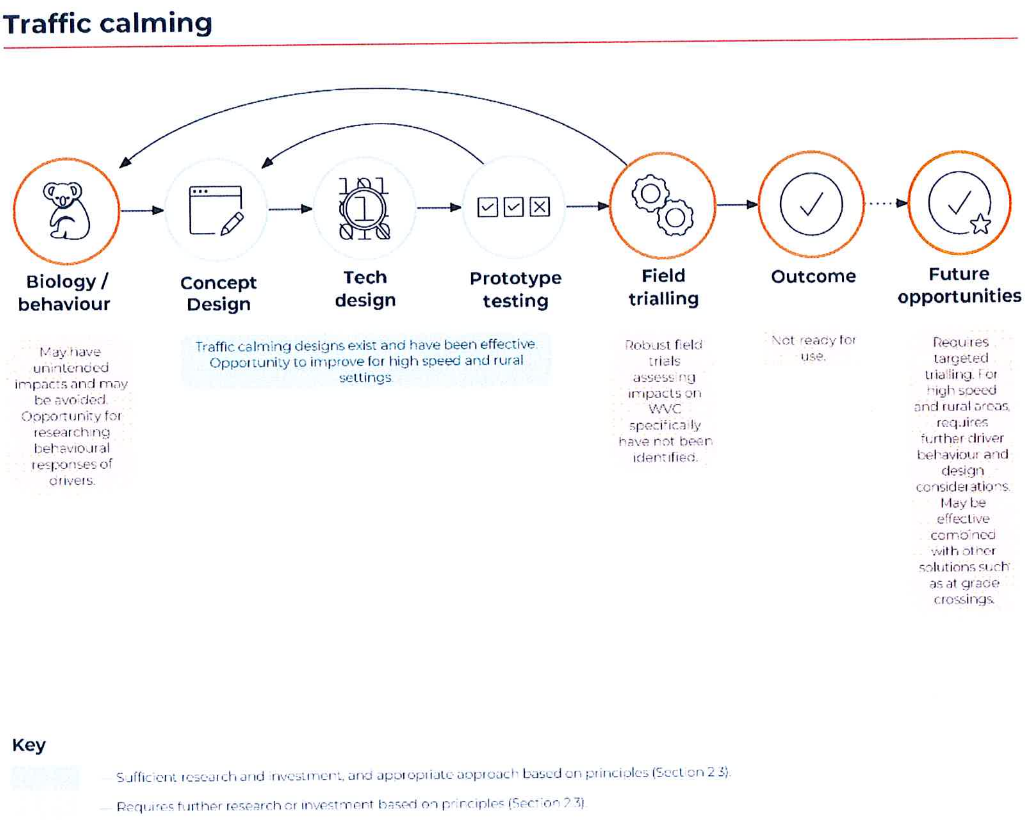

Figure 3.4 Qualitative assessment of traffic calming and speed reduction at reducing rates of WVC and identification of areas for further research and development.

4 Evaluation of signal-based approaches

4.1 Targeting wildlife

4.1.1 Wayside deterrents

Wayside deterrents that target wildlife are installed on the sides or verges of roads and railways and aim to warn wildlife of oncoming traffic and typically encourage them to either move away from the vehicle or to not enter the road or railway.

4.1.1.1 Reflectors

Wildlife warning reflectors (hereafter referred to as reflectors) are a small unit containing reflective mirrors and coloured lenses that are mounted on posts on the side of roads and railways (Figure 4.1). They are strategically spaced along both sides of the road so that light from oncoming vehicle headlights are reflected across the road (and possibly onto the opposite reflectors) through a brightening arc and towards road verges. Depending on the type of reflector, the light may be perceived as a warning flash or as a continuous barrier of light (Bender 2001a). It is suggested that reflectors provide a visual warning to animals and modifies their behaviour by discouraging them from attempting to cross the road or railway or increases their awareness of approaching vehicles.

Figure 4.1. Examples of different types of reflectors installed on roadsides to reduce rates of WVC. Source: Marcel Huijser, in D'Angelo and van der Ree (2015)

Reflectors are an appealing mitigation measure because they are low cost, easy to install and they don't form a permanent continuous barrier to the movement of wildlife. Reflectors for reducing WVC have existed since the early 1960s and have mostly been used in Europe with studies testing the effectiveness of the device on ungulates and smaller mammals likes hares and foxes (D'Angelo et al. 2006, Benten et al. 2018, Jasińska et al. 2022).

Despite being marketed as a proven and humane solution to reducing WVC, the effectiveness of reflectors largely remains unproven with many studies observing no change to WVC rates (Brieger et al. 2017, Benten et al. 2018), reporting inconclusive results or lacking scientific rigour (D'Angelo et al. 2006, van der Ree et al. 2015c, Grumert and Nusia 2023). There are no scientific trials of reflectors in Australia, apart from a test on captive red kangaroos and red-necked wallabies, which found the behavioural response was negligible and reflectors would be of little value in reducing rates of WVC of these two species (Ramp and Croft 2006).

One limitation of reflectors is that the colour and intensity of light produced by reflectors may not elicit a response in the target species, namely because behavioural responses to stimuli may differ among species, and even between individuals

(D'Angelo and van der Ree 2015). For example red is a commonly marketed colour for wildlife reflectors. However, most marsupials lack sensitivity to long wavelengths (i.e. red light) and would therefore likely be undeterred by the warning lights produced by red reflectors (D'Angelo and van der Ree 2015). This lack of apparent suitability is not surprising because most reflectors were developed in Europe for ungulates and were not specifically designed for Australian fauna.

There is also evidence to suggest that some animals may become habituated to repeatedly occurring light from reflectors (Ujvari et al. 1998). In contrast, the results of one study on the effectiveness of reflectors on deer behaviour reported increased rates of WVC in areas where reflectors were installed (D'Angelo et al. 2006). One possible explanation is that the light from reflectors, combined with vehicle headlights, overwhelmed the animals' visual system (D'Angelo and van der Ree 2015). Importantly, the use of increased light as a mitigation to WVC needs to be balanced with the potential impact on sensitive species.

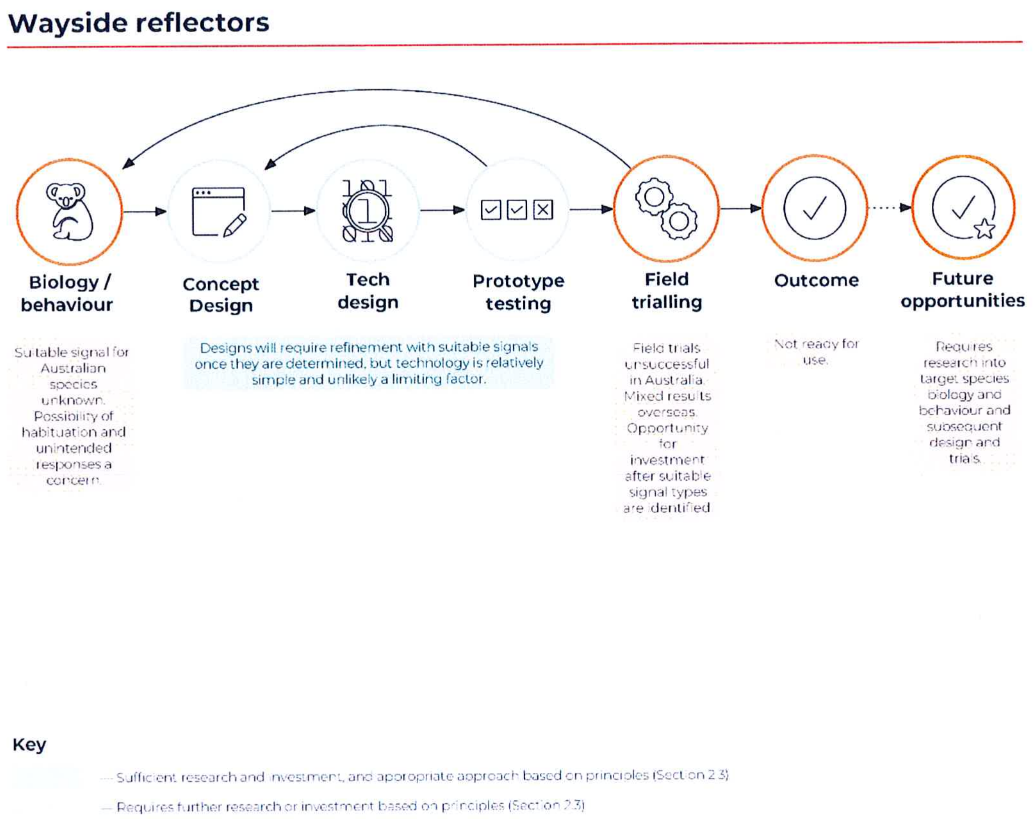

Figure 4.2 Qualitative assessment of reflectors at reducing rates of WVC and identification of areas for further research and development.

4.1.1.2 Chemical repellents

The use of chemicals and other repellents to discourage animals from entering specific areas or undertaking certain undesirable activities is a common approach in a wide range of situations, including crop protection, human-wildlife conflict, airports, fisheries and human disease control (e.g. DeLiberto and Werner 2024). Chemical repellents often focus on taste, which may result in a gastrointestinal malaise or be bitter, contain particulates, putrescent eggs or predator excretions (Bíl et al. 2018). Odour repellents are typically associated with the smell of potential predators, such as urine or excrement, and are intended to either raise awareness and vigilance or repel the target species.

The use of chemical repellents to discourage wildlife from entering roads and railways have been tested in a relatively small number of studies in Europe with mixed results that varied among species (Rea 2003, Hedlund et al. 2004, Andreassen et al. 2005, Kušta et al. 2015, Carvalho et al. 2017, Bíl et al. 2018). One of the most recent and scientifically robust trials of odour repellents was conducted in the Czech Republic over 30 weeks with five phases of monitoring of rates of WVC of large mammals (roe deer, red deer, wild boar) before and after the implementation of an odour at both control and impact sites with similarly high rates of WVC (Bíl et al. 2018). The odour was a commercial product intended to repel deer and was applied to wooden poles at 80 cm above the ground. The study found that rates of WVC decreased by 26 – 43% where the repellent was applied, which was up to three times lower than that claimed by the manufacturer (Bíl et al. 2018). Another study in the Czech Republic found rates of WVC on roads and railways was reduced by 37% after applying three different odours, however the study did not include control sites in the study design, limiting the broadscale applicability of the results (Kušta et al. 2015).

Roadsides are identified as attractive places to forage or move along for a wide range of species, including kangaroos in Australia and ungulates in Europe and North America (Rea 2003, Lee et al. 2015). Chemicals have been applied to vegetation to make them less palatable to herbivores, but is considered semi-effective and typically not feasible across the vast road and rail network where species feed (Rea 2003).

While chemical repellents may result in a small reduction in rates of WVC in certain situations, the feasibility of widespread application is limited due to:

- The need to apply chemicals at stations in close proximity (spacing in trials typically 7 – 10 m apart) and regularly re-apply the chemical to maintain effectiveness, especially during periods of high rainfall.
- The risk of habituation of fauna to the chemical repellents.
- The need to find chemicals that are effective at deterring the target species without causing injury or death of both target and non-target species.
- Challenges associated with applying the treatments over large areas.

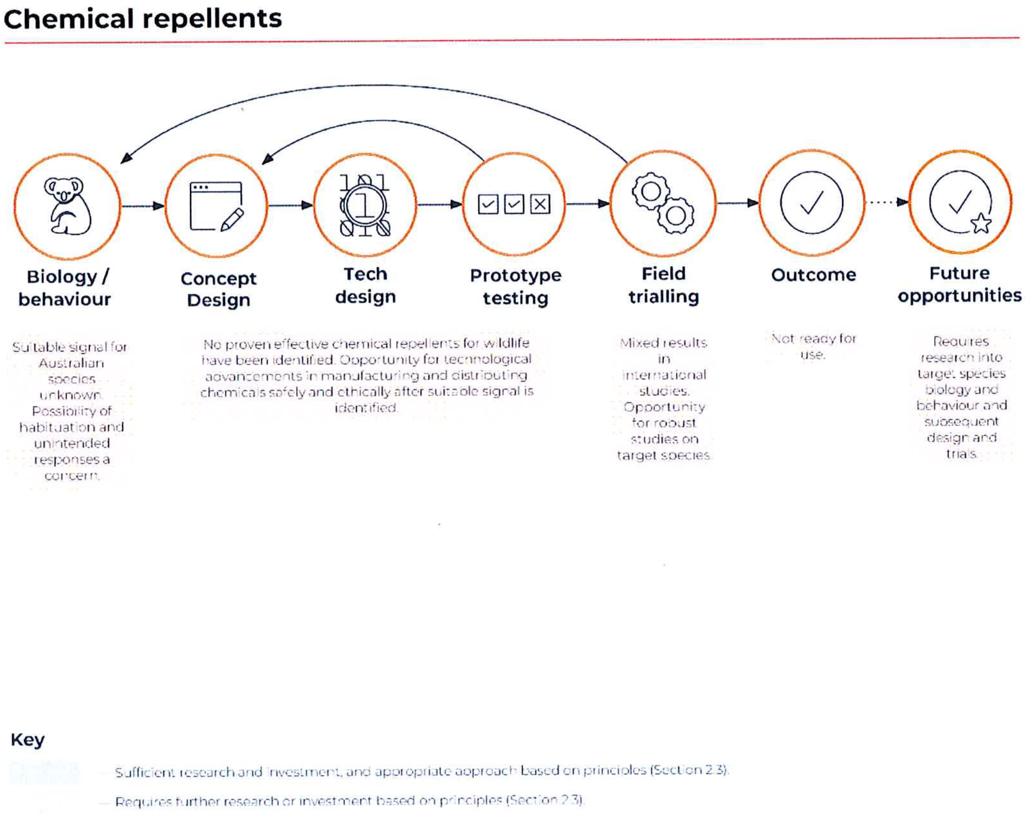

Figure 4.3 Qualitative assessment of chemical repellents at reducing rates of WVC and identification of areas for further research and development.

4.1.1.3 Electric mats and wildlife guards

Electrified mats are embedded in the road surface and are often used as a modern alternative to traditional cattle guards which may trap fauna and their legs, can be leapt over by some species, and pose a sliding hazard to motorists and cyclists (Allen et al. 2013, Gagnon et al. 2020). Double cattle guards can resolve the leaping issue for most mammalian wildlife, however, is expensive to install and poses a greater sliding risk to cyclists than single cattle guards (Gagnon et al. 2020). Therefore, electric mats may be more suitable than cattle grids or modified wildlife grids in many situations. However, there are few peer-reviewed publications of electric mats and most trials have been undertaken in North America (Allen et al. 2013, Gagnon et al. 2020, Huijser 2024) and none have been trialled in Australia.

Electric mats are primarily installed in tandem with wildlife exclusion fencing – at fence ends and gaps where roadways or driveways intersect fence lines (e.g. Figure 4.4, Figure 4.5) – and at-grade crossings (TRB 2021). Electric mats are intended to function as an alternative to gates which are commonly installed at fence gaps but regularly left open allowing wildlife to enter the road or rail corridor (Huijser & Getty 2023). The design avoids entrapment of wildlife legs; electrified mats are designed to deliver a painful shock to wildlife upon contact – but are not harmful to vehicles or pedestrians wearing shoes – which functions as a painful and psychological barrier to deter fauna attempting to utilise the electric mat for passage onto roads and railways (Gagnon et al. 2020). Electrified mats can be powered by mains electricity supply, solar panels, or battery combinations; this flexibility in power generation is intended to facilitate both peri-urban and remote applications.

Figure 4.4 Electric mat deployed on an at-grade crossing in North America. (Gagnon et al. 2020)

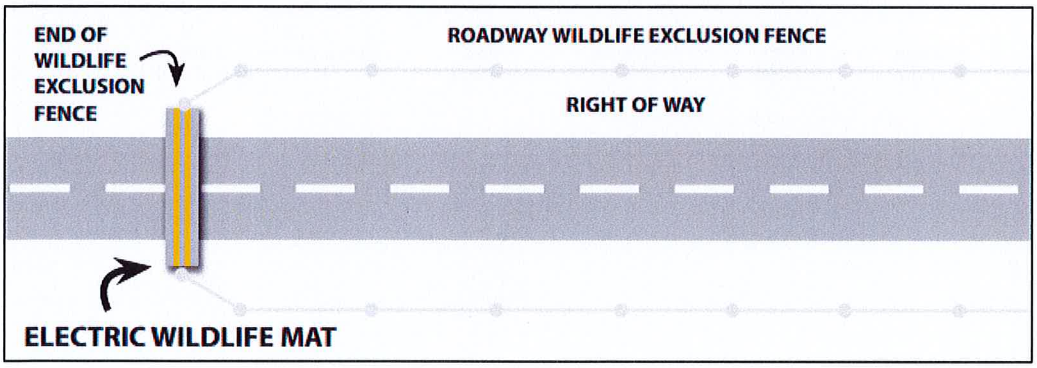

Figure 4.5 Diagram of electric mat design to be used with end of wildlife exclusion fencing. *Crosstek.*

Design and construction materials vary among applications, with more durable electrified concrete on roads with high traffic volume and heavy load vehicles and composite materials for secondary roads with lower traffic loads (Gagnon et al. 2020). For instance, CrossTek (2012) have developed an electric wildlife mat 'ElectraMat(TM)' available in concrete and composite material varieties, the latter consisting of durable recycled plastic and fiberglass mixtures. Likewise, Bearier Solutions (2023) have developed an electric mat product, consisting of vulcanised rubber and galvanised and stainless steel, to deter bears from entering residential properties in the United States.

There is promising evidence to suggest electric mats effectively excludes wildlife from fenced road corridors, however further research is needed to determine efficacy in Australia. A recent study in Montana, United States, examined the efficacy of various types of electric barriers in excluding black bears from roadside crops; in all six events, black bears were prevented from traversing an electric mat, which was installed at a gap in a wildlife fence along a low-volume access road (Huijser & Getty 2024 in press). Following unsuccessful attempts to breach electrified barriers, black bear attempts to enter other access points and overall presence in the vicinity decreased. Therefore, electric mats might also be effective in modifying wildlife behaviour and movement as a form of aversive conditioning.

There is a scarcity of published literature assessing whether ungulates can sense electric fields associated with activated mats and fences (Gagnon et al. 2020) and further field studies are necessary before electric mats can be considered an effective WVC mitigation measure. Given the emerging nature of electric mats, longevity and maintenance requirements are not yet known, particularly across climatic contexts.

Electric mats have not been trialled in Australia but are likely effective for species that walk (e.g. koala) and probably less effective for species that hop, such as kangaroos. Electrified mats must be at least 4.6 – 6.6 m in width to prevent fauna in North America from jumping across and bypassing the electric shock (Huijser & Getty 2022). The capacity of electric mats to decrease WVC must also be balanced against conservation values because electrified mats have the potential to kill small animal species such as amphibians, reptiles, and small mammals (Huijser & Getty 2024 in press). Systems that only function in the presence of the intended target species (i.e. with an animal detection system) may eliminate this risk, but they are yet to be trialled (Huijser & Getty 2024 in press). Developments of this solution should focus on small scale implementation with specific goals and target species. The ideal signal strength for the target species will also need to be determined, and any unintended impacts such as injury to the target or non-target species considered.

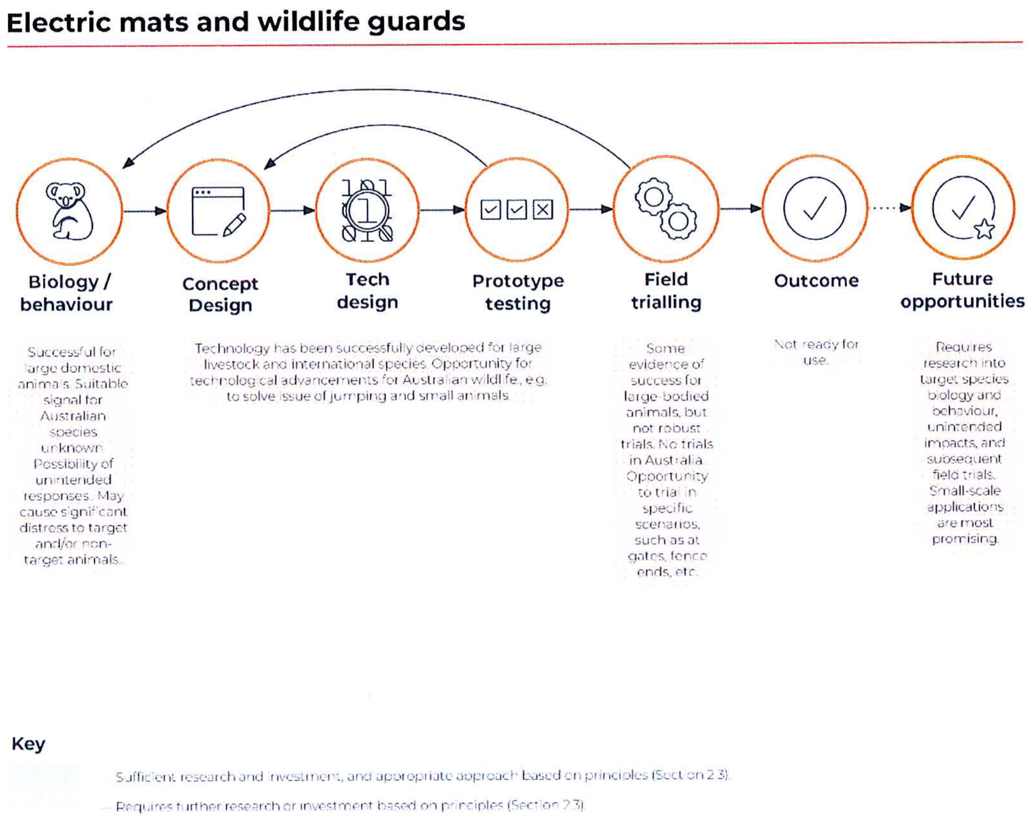

Figure 4.6 Qualitative assessment of electric mats and wildlife guards at reducing rates of WVC and identification of areas for further research and development.

4.1.2 *Vehicle-borne deterrents*

Vehicle-borne deterrents are mounted at the front of cars, trucks and trains and emit noise as the vehicle moves, alerting animals to the presence of the vehicle and warning them to not enter the road or railway or move away.

4.1.2.1 Acoustic deterrents

Acoustic deterrents include whistles, horns, sirens and other noises to deter wildlife and are typically passive (wind-driven) or active (electronic) (Bender 2001b). Similar to reflectors, acoustic deterrents theoretically work by warning animals of the approaching vehicle and increasing their vigilance. When vehicle mounted, they are typically mounted to the front of vehicles and emit a high frequency noise as the vehicle is driven. Simple air-activated whistles are relatively cheap and electronic systems more costly. More recently, battery-operated devices have been developed that produce and propagate noises, even when the vehicle is stationary (D'Angelo and van der Ree 2015).

Vehicle mounted whistles were first invented in 1979 in Austria (Romin and Dalton 1992) and have since been widely distributed and used in North America and Europe for deer and in Australia for kangaroos (D'Angelo and van der Ree 2015). However, there is little scientific evidence to indicate that current warning whistles are effective at modifying animal behaviour and reducing rates of WVC (Muzzi and Bisset 1990, Romin and Dalton 1992, Bruinderink and Hazebroek 1996, Bender 2001b, Scheifele et al. 2003, Valitski et al. 2009).

A key limitation of whistles is that the distance to which the high-frequency ultrasonic noises can be heard is unlikely to extend far enough in front of fast-moving vehicles to give the animal sufficient time to respond and move away from the road (Bender 2001b, Scheifele et al. 2003). Ultrasonic noises have higher attenuation rates that sonic or infrasonic noises, further challenging the marketing claims of these products. This limitation is further impacted by factors like environmental conditions, land topography and vehicle noise which can all reduce the distance of, or mask, the high-frequency sounds. It's also well known that animals can become habituated to noises over time (Bomford and O'Brien 1990).

One such example of an auditory deterrent used in Australia is the Shu Roo. Invented in 1985 and first available in 1989, the Shu Roo is marketed as an ultrasonic deterrent device that warn kangaroos of approaching vehicles by creating a "pattern" of high-frequency sound. The manufacturer claims the warning noise can be heard for approximately 50 metres on each side of the vehicle, and for 400 metres ahead of the vehicle (ShuRoo 2024).

A study on the efficacy of the Shu Roo on eastern grey kangaroos and red kangaroos found that the device produced both audible and ultrasonic frequencies. While static field tests showed the signal was just detectable at a distance of 50 m, driving tests revealed the Shu Roo signal was not detectable above the noise produced by the moving vehicle (Bender 2001b). The study also observed kangaroo behaviour in response to the Shu Roo and determined that it did not alter their behaviour, possibly because it was outside their hearing range (Bender 2001b). A subsequent study of the effectiveness of the RooGuard® (Model Mk II) at deterring tammar wallabies from a known source of food was similarly not effective (Muirhead et al. 2006).

An important consideration in designing and testing whistles and other vehicle-mounted auditory deterrents for a specific target species is that the noises are within their hearing frequency range, are audible, perceived as an undesirable sound and elicits an appropriate response. In addition, the acoustic deterrent must be propagated far enough in front of the moving vehicle to give the target species sufficient time to hear the signal, respond appropriately and avoid the WVC.

Volkswagen are currently developing a vehicle-mounted deterrent for macropods, focussing on eastern grey kangaroos initially (Roobadge | Volkswagen Australia). Field-based trials are currently underway, and the noises being tested include naturally occurring and biologically relevant signals such as predator sounds, alarm calls from other species and the 'foot thump' that kangaroos use to warn other kangaroos of danger. No published results are currently available, but the approach adopted by the developers is consistent with the development and evaluation framework recommended in this review, ensuring any results of trials will have high degree of reliability.

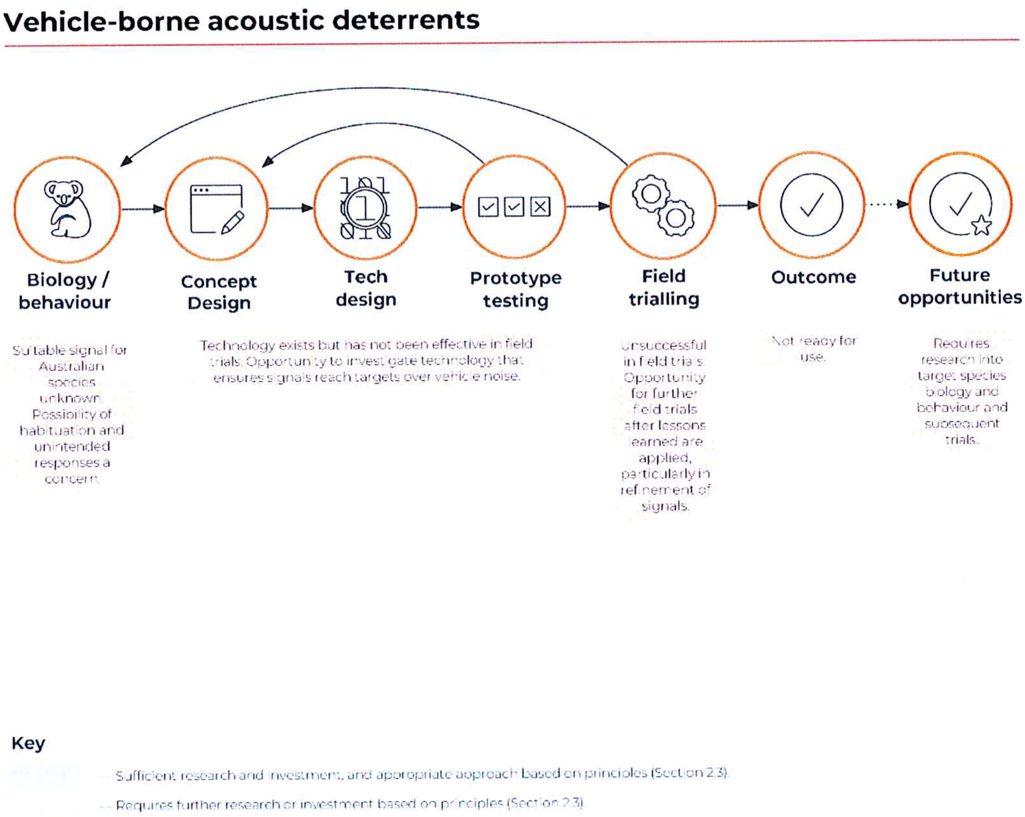

Figure 4.7 Qualitative assessment of vehicle-borne acoustic deterrent at reducing rates of WVC and identification of areas for further research and development.

4.1.2.2 Vehicle lighting

Forward-facing lighting on vehicles is typically intended to improve the detectability of wildlife by drivers, rather than deterring wildlife from the road or roadside (Section 4.2.1.3). One study tested the use of rear-facing vehicle lighting which illuminated the front of the vehicle (Figure 4.8) and makes it more visible to wildlife (DeVault et al. 2020b). The theory is that freeze responses will be lessened if fauna can see the vehicle, rather than just the headlights. The study, undertaken in the USA over a 14-month period found that the likelihood of a dangerous deer–vehicle interaction decreased from 35% of vehicle approaches using only headlights to 10% of vehicle approaches using the light bar that illuminated the front of the vehicle. The reduction in dangerous interactions appeared to be driven by fewer instances of immobility (freezing) behaviour by deer. Future work should explore fine-tuning the lighting signals regarding the visual capabilities of target species and examining the responses of wildlife to the illuminated vehicle, particularly for erratically moving Australian species such as kangaroos. If this solution can be implemented as intended it could be a cost-effective, wide-ranging solution that could result in small but significant reductions in WVC. Compared to other vehicle-borne deterrents such as noise, this solution could also have fewer unintended impacts to roadside habitat.

Figure 4.8. Set-up of vehicle illumination intended to increase the detectability of oncoming vehicles for wildlife, as used in the study by DeVault et al. (2020a).

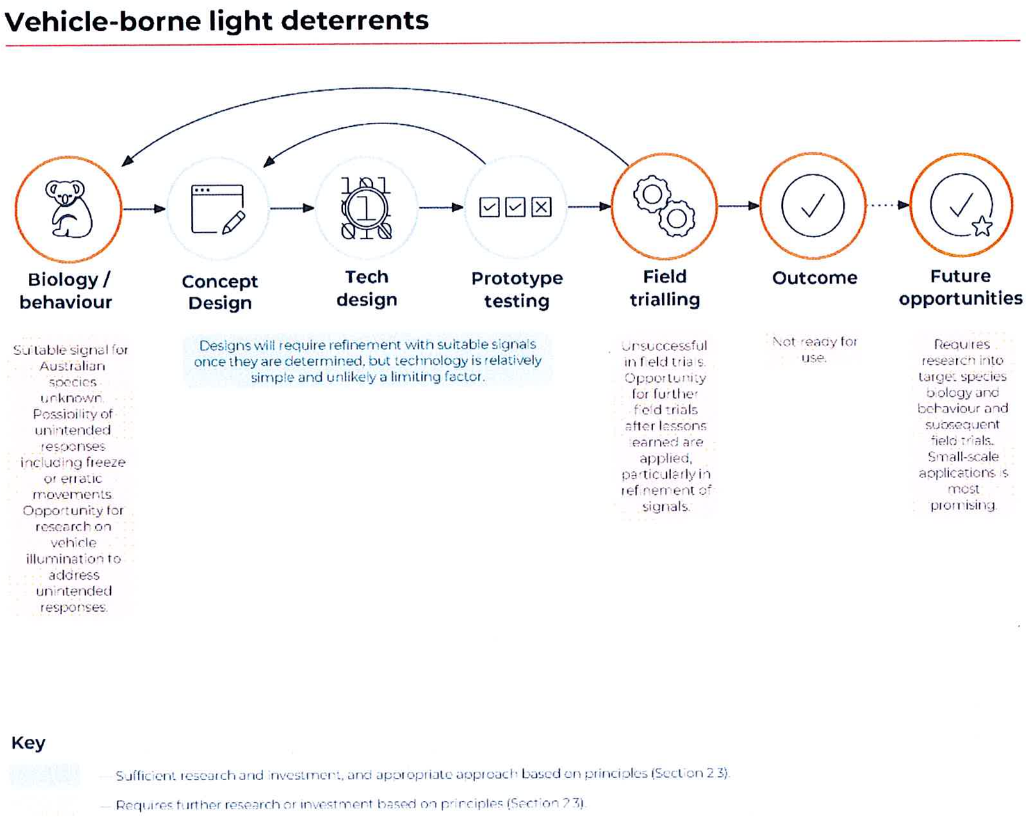

Figure 4.9 Qualitative assessment of vehicle-borne light deterrents at reducing rates of WVC and identification of areas for further research and development.

4.2 Targeting vehicle operators

4.2.1 Wayside signals

Wayside signals are installed on the side of roads and railways and are intended to warn motorists and train drivers of the presence of wildlife and encourage drivers to modify their driving. The most common wayside signal is wildlife warning signage, which are the most utilised, widespread, and earliest forms of WVC mitigation measures (Huijser and McGowan 2003, Bond and Jones 2013). Tryjanowski et al. (2021)'s global review of wildlife warning signs tracks the introduction of wildlife warning signs to the 1931 Convention on the Unification of Road Signals Geneva where WVC was already perceived to be costly in terms of vehicle repair and animal value.

The primary goal of wildlife warning signs is to improve driver safety by reducing the incidence and severity of WVC; wildlife warning signs do not impede wildlife movement on roads (Huijser et al. 2015). Wildlife warning signs are designed to modify driver behaviour by either cautioning drivers to be attentive to the potential presence of wildlife on the road and associated increased risk of WVC, or informing drivers of enforced or advisory speed reductions (Huijser et al. 2015).

4.2.1.1 Static signage

Standard wildlife warning signs (Figure 4.10) are generally designed in the same style and size dimensions as other road warning signs, which often varies by country or region. Relatively inexpensive, these signs are commonly installed in road sections which have experienced high counts of WVC incidents and are often static (meaning 'unchanging'). Static signs typically depict a silhouette of a large mammal species common to the region which poses a safety concern for drivers such as deer or kangaroos, a smaller species regularly impacted by WVC, or a species of local conservation concern on a bright-coloured background (Huijser et al. 2015). Variations of static signage include additions of distance in which motorists can expect increased risk of animal encounters and brief accompanying descriptions (e.g. cow silhouette, unfenced cattle next 5 km - Figure 4.10). Enhanced and intelligent signage are discussed in Sections 4.2.1.2 and 5.3.1.1.

Figure 4.10. Examples of static wildlife warning signs with increasing (from left to right) levels of information for motorists. Photos by Rodney van der Ree, WSP.

Despite widespread global uptake, there is limited and inconsistent empirical evidence that wildlife warning signage is an effective WVC mitigation measure with little to no causative change in vehicle speed (Bond and Jones 2013, Huijser et al. 2015). Whilst there is evidence of a significant decrease in the rate of WVC in North America when warning signage is accompanied by an enforced speed limit (Langley et al. 2006, Found and Boyce 2011), there was no evidence in a trial study to suggest that warning signage, installed alongside time-specific speed limit reductions, reduced WVC mortality of koalas in South East Queensland (Dique et al. 2003).

Static signage is not endorsed as a stand-alone, effective, or long-term solution. It has been hypothesised that most drivers do not modify their behaviour in response to standard signage because they seldom detect fauna and therefore do not trust the sign (Huijser et al. 2015). Ironically, the probability of observing wildlife decreases if signs were effective at reducing rates of WVC, which would further undermine the effectiveness of the sign (Huijser et al. 2015). In addition, a substantial shortcoming of static signage is driver habituation and subsequent disregard to signs over time (Krisp and Durot 2007, Tryjanowski et al. 2021). Signs are rarely removed, even if the problem is no longer relevant, contributing to an overabundance of wildlife warning signs which further minimises their effectiveness (Huijser et al. 2015). Oversaturation of signs should also be avoided by targeting their installation to key WVC hotspot locations (Huijser et al. 2015).

Static signage

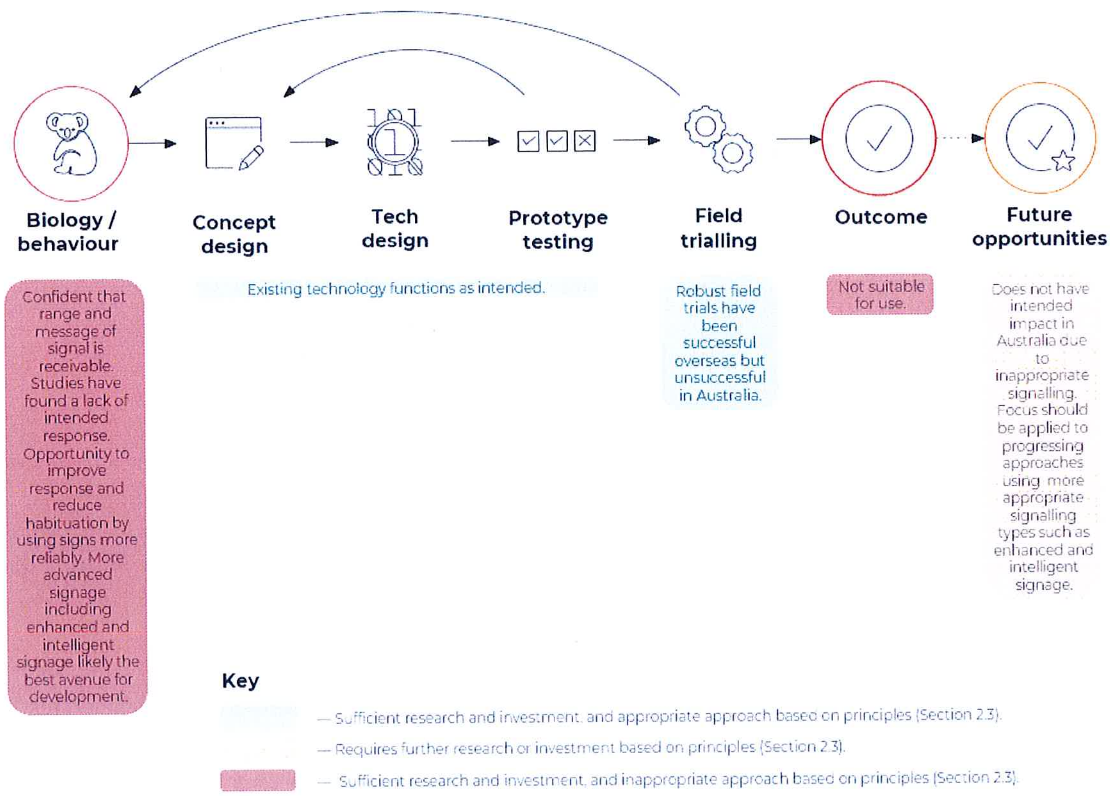

Figure 4.11 Qualitative assessment of static signs at reducing rates of WVC and identification of areas for further research and development.

4.2.1.2 Enhanced signage

Enhanced wildlife signs combine elements of static signs and dynamic signs, where dynamic signs display variable messaging or information. Dynamic signs can be controlled manually or activated automatically by animal detection systems (i.e. refer to intelligent signs – Section 5.3.1.1). Enhanced signs are generally larger than standard signs and can be permanently installed, installed during high-risk times of the year and removed during low-risk periods, or activated at certain times of the day when wildlife are most active (e.g. from dusk till dawn) (Huijser et al. 2015). Enhanced signs are installed at the same locations as standard signs.

Empirical evidence indicates that drivers detect and recall enhanced warning signs more than standard signs because of the perceived significance of the stimuli (Summala and Hietamäki 1984). Enhanced signs often include flashing coloured lights, attention-grabbing or disturbing illustrations (e.g. depicting WVC), images of charismatic or endangered species, variable messaging including rates of WVC (historical or near real-time) and/or other non-WVC related road warnings (Huijser et al. 2015). These features are intended to gain the attention of drivers to inform them about the impacts of WVC to driver safety and wildlife conservation and subsequently lower vehicle speeds. The effectiveness of signs warning of camel-vehicle collision risk in Saudi Arabia was influenced by the design of the sign (Al-Ghamdi and AlGadhi 2004). In another example, Del Frate and Spraker (1991) used road signs with a running tally of the rate of moose-vehicle collisions as part of their WVC mitigation program during the 1990-1991 winter in Alaska. This approach is likely to be more effective than standard road signs, as almost three-quarters of Australian drivers that were surveyed said they would be more likely to respond to wildlife warning signs that displayed updated roadkill data (Bond and Jones 2013).

Temporal wildlife warning signs are installed or activated at specific times of the day (e.g. dawn or dusk) or year at specific road sections to warn drivers of wildlife presence during heightened hazardous conditions or high-activity periods (Huijser et al. 2015). These signs are generally species-specific and only operate in periods of increased WVC risk or impact to the species of conservation value. Figure 4.12 depicts signage specific to the migratory short-tailed shearwater during its fledging period on Phillip Island in Victoria where signs are erected for a few weeks each year and then removed. A three-year study of WVC occurrence in Tasmania found a significant relationship between rates of WVC and specific times of day, specific locations and vehicle speed (Hobday and Minstrell 2008). The authors suggested that modifying driver speed at specific times of day and at specific location could significantly decrease the occurrence of WVCs, and this could be achieved through enhanced signs (Hobday and Minstrell 2008).

Road stencilling and pavement markings are a relatively inexpensive form of signage intended to identify areas of high wildlife activity and alert drivers to the associated WVC risk. Road stencilling and pavement markings are designed to be attention-grabbing, often employing bright colours with simple text and/or animal silhouettes (Figure 4.13). Road stencilling and pavement treatment are increasingly employed in Australia; for instance, the Green Infrastructure Guidelines developed by the City of Moreton Bay Council (2023) in Queensland outlines the application of pavement treatments to provide driver cues and modify driver behaviour in areas where wildlife are likely to cross the road. Light-coloured pavement on roads which potentially increases the detectability of wildlife to motorists (Section 4.2.1.3), may also serve as a general warning to drivers if accompanied by signage and education. However, light-coloured pavement is also used to reduce ambient temperatures by reflecting heat and these two purposes may cause confusion and limit its ability to consistently warn motorists of increased risk of WVC.

Figure 4.12 Enhanced roadside wildlife warning sign, specific to the Short-tailed Shearwater, installed for a few weeks per year at Phillip Island, Victoria, Australia.

Source: Rodney van der Ree, WSP

Figure 4.13 Enhanced roadside wildlife warning sign, specific in location and time of year to warn road-users of WVC risks associated with deer migration routes.

Source: International Wildlife Film Festival Ltd

While enhanced signs are more effective than standard signs, motorists can also become habituated to enhanced signs (Tryjanowski et al. 2021), resulting in reduced effectiveness.

A study of the effectiveness of signs with nighttime-activated flashing beacons spaced 8 km apart on roads which intersected deer migration paths found that while drivers consistently reduced their speed, the speed reduction was minimal and no reduction on deer-vehicle collisions was found (Riginos et al. 2022). A trial of signs in Saudi Arabia found speed reductions were typically modest, and ranged between 1.93 – 6.51 $kmhr^{-1}$ (Al-Ghamdi and AlGadhi 2004)

However, even small levels of speed reduction can be crucial to WVC mitigation. Several studies have found that small reductions in vehicle speed can provide a substantial decrease in the rate and severity of road accidents (Finch et al. 1994, Taylor et al. 2002). A combination of strategies could improve vehicle speed reduction to reduce WVC, which is consistent with study findings in British Colombia, Canada, which observed a 58% decrease in moose-related WVC after large moose-related WVC signs were installed at collision hotspots in tandem with a public awareness campaign (Rea 2012).

Most field trials of signage have focussed on measuring reductions in vehicle speed, without assessing changes to rates of WVC or other behaviours such as driver vigilance. A recent study that assessed these outcomes found significant change in behaviour – including speed reduction and increased vigilance – with enhanced signage present, as well as a significant decrease in the likelihood of WVC from 36% to 2% (Collinson et al. 2019). The study also found that speed and distance between the sign and the animal significantly influenced results, with 100 m the most effective distance.

Enhanced signage may reduce WVC provided they are well-designed and placed in high-risk locations and at high risk times of the day or year. The biggest limitations relate to driver habituation and relatively modest reductions in vehicle speed. Some of these limitations could be overcome by moving towards intelligent signage (Section 5.3.1.1), which provides more reliable signals by using real-time animal detection systems. A driver awareness program (Section 4.2.3.1), advising them of appropriate responses to activated signs, would also be required to maximise effectiveness.

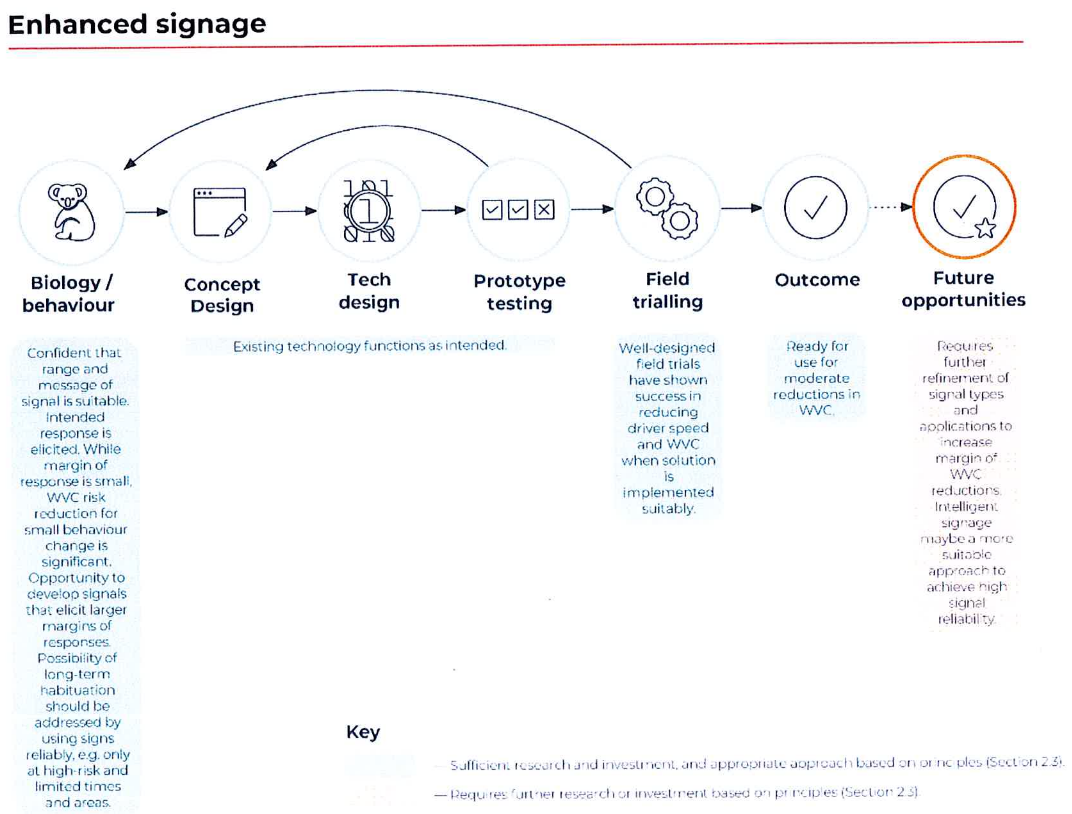

Figure 4.14 Qualitative assessment of enhanced signs at reducing rates of WVC and identification of areas for further research and development.

4.2.1.3 Wayside lighting and other measures to improve the detectability of wildlife by motorists

The visibility and detectability of wildlife to motorists and of vehicles to wildlife impacts the rate and severity of WVC because it affects the amount of time for motorists and/or wildlife to respond. The detectability of wildlife to motorists can be enhanced through wayside lighting – typically overhead lighting – or making road surfaces lighter in colour to contrast more with darker-coloured animals. Theoretically, increased visibility and detectability should reduce rates of WVC if vehicle operators and/or wildlife respond appropriately and with enough time for the response to avoid the collision (Hobday 2010). This approach is more feasible on roads than railways because trains can travel at higher speeds and take longer to slow down that cars and trucks.

Wayside lighting involves illuminating the road or railway, typically using overhead lighting, to improve visibility and detectability of wildlife by vehicle operators and conversely, the visibility and detectability of vehicles by wildlife.

A study conducted in the 1970's in Colorado, USA, illuminated a section of highway with overhead street lights for 1-week on and 1-week off between January and April when deer were most prevalent in the area (Reed and Woodard 1981). The trial included the presentation of a full-sized taxidermised deer and observations were made of the number of deer crossing the road, vehicle speeds, motorist behaviour (i.e. did vehicles slow down) and the number of deer-vehicle collisions. Neither the speed of motorists or the rate of deer-vehicle collisions (measured as rate of collisions per crossings) differed significantly during the lit and unlit phases of the trial (Reed and Woodard 1981). Importantly, highway lighting did not affect where deer chose to cross, but it appeared that more deer chose to cross the highway in the lit areas after the trial commenced and when the lights were turned off. The study concluded that increased lighting levels were not effective in reducing the rate of deer-vehicle collisions.

A more recent study on a single-lane sealed road through forest habitat on the outskirts of Hobart, Tasmania placed nine taxidermized mammals on the road and conducted controlled trials testing the effects of headlight strength on nighttime driver detection distances (Hobday 2010). Motorists drove at 10 – 15 km hr^{-1} and repeated trials with their high beam or low-beam headlights and were asked to stop as soon as they detected the taxidermised animals on the edge or centre of the road, enabling the reaction time and stopping distance to be calculated. The detectability of the nine species by motorists varied among species and between the high- and low-beam scenarios. The size of the animal (ranging from a wallaby to bandicoot) was not a significant variable influencing detectability, however fur reflectance was significant. The endangered Tasmanian devil had the shortest mean detection distance on high beam (61 m) and the second shortest on low-beam (34 m), resulting in safe stopping speeds of 54 km hr^{-1} and 38 km hr^{-1}, respectively.

A more realistic study using free-ranging wildlife (primarily white-tailed deer, wild pigs and various small mammals) and typical driving speeds (70 – 90 km hr^{-1}) was recently completed in South Carolina, USA (Pakula et al. 2023). The trial used a forward-looking infrared camera and a rear-looking camera mounted to a typical USA vehicle (Ford 150) to record each trial. Detection distances increased by 21 m when using high-beam headlights and by 23 m when deer were moving, and yet every encounter with deer, pigs and small mammals were considered dangerous and likely to result in a collision. Importantly, this study concluded that most drivers cannot safely detect deer, wild pigs or small mammals at night (Pakula et al. 2023).

All trials considering illumination and wildlife detectability have essentially concluded that on most roads with speeds > ~70 km hr^{-1}, most drivers are unable to consistently detect even large-sized wildlife and even when they do, they have insufficient time and space to slow down and avoid the WVC (Rodgers and Robins 2006, Hobday 2010, Mastro et al. 2010, Pakula et al. 2023). At the very least, reduced speeds should reduce collision severity and the outcome for both people and wildlife, however this has not been reliably quantified. One study that tried to evaluate the effect of vehicle speed on the severity of koala-vehicle collisions was unable to quantify the effect because there was no observed reduction in vehicle speeds due to signage (Dique et al. 2003).

Clearing of roadside vegetation has also been suggested as an approach to reduce WVC by increasing detectability of wildlife by motorists and providing more time and longer distances to slow down. This approach also theoretically gives wildlife more time to detect and avoid approaching vehicles, but there are no trials explicitly testing the effectiveness of this approach.

Making the road surface whiter may improve the detectability of wildlife on the road by increasing the contrast between the dark fur of many animals and the light colour of the road. There has been no research specifically on this topic, and further investigation is warranted. Key considerations should measure the species-specific detectability; weather, road and traffic conditions; the response times and the subsequent reduction in the rate and severity of WVC.

Limitations of illumination and detectability of wildlife are:

— Animals with large body sizes are probably more detectable than smaller animals, but most motorists are unable to consistently detect even large animals, such as deer, on roadsides.

— Even if animals could be detected, most drivers will not be able to slow down in time to avoid the collision.

— Any unintended consequences of increased illumination, roadside mowing or painting road surfaces a light colour. For example, extensive illumination using overhead street lighting will have other negative ecological effects and the accepted advice is to reduce, rather than increase, light levels at night, especially in nature conservation areas (e.g. Rich and Longcore 2006, Stone et al. 2015, Lockett et al. 2021, DCCEEW 2023).

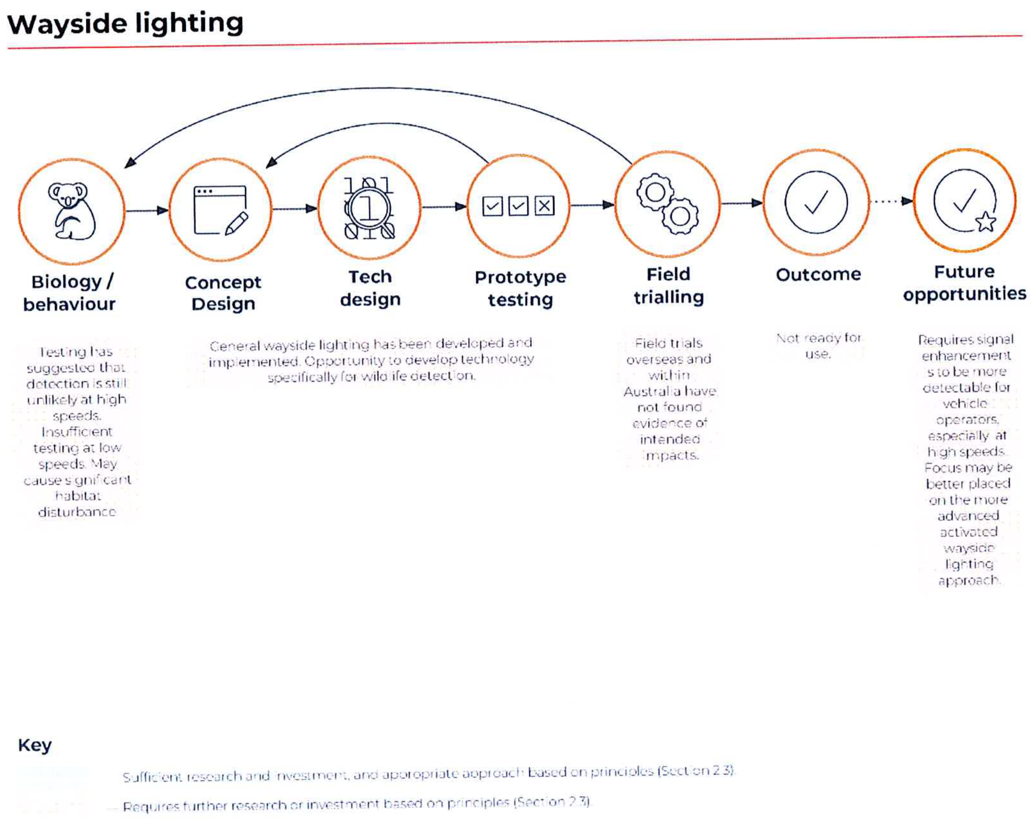

Figure 4.15 Qualitative assessment of measures to improve the detectability of wildlife by motorists at reducing rates of WVC and identification of areas for further research and development.

4.2.2 *In-vehicle signals*

In-vehicle signals are delivered to motorists via devices inside the car, such as in-built satellite navigation systems or smartphone applications. These in-vehicle applications can be sent when the car enters a specific area at a specific time of day or year (Section 4.2.2.1) or can be sent when an animal is detected (Section 5.3.2).

4.2.2.1 Location-based applications

In-vehicle signals without animal detection systems utilise the location of the vehicle or driver and information inputs such as WVC hotspot mapping, wildlife sightings, collision statistics, and environmental factors like time of day or year to warn drivers of high-risk WVC locations or areas. The signals can come from an in-car global positioning system (GPS)/satellite navigation system or a smartphone. This signalling style is like that of enhanced signage, but with the added benefits of increased adaptability, wider application across roads and railways, and cheaper build and maintenance costs. Limitations of location-based technology includes the need for user uptake (e.g. downloading the app and opening it each trip), access to technologies such as smartphones or compatible vehicles, communication services (e.g. cellular data or GPS coverage) and knowledge of WVC hotpots.

Areas with high risk of WVC can be identified through the identification of collision hotspots and knowledge of wildlife abundance. Hotspots can be mapped by analysing existing WVC data and identifying where there is a higher density or incidence of WVC. The spatial and temporal scale of WVC hotspots can vary geographically and overtime. In some areas, the hotspot might be restricted to a short length of road (in the tens or hundreds of metres) when the habitat and animal movement pathways are clearly defined. In other areas, when habitat is widespread and animal movement is more diffuse, the hotspots might extend over a few kilometres or more. Importantly, hotspots can and should change over time – if rates of WVC are high, the local animal population should decline until it is no longer a hotspot, and then it increases again if or when the population recovers. Similarly, a location may be a hotspot for a season when the species is present and at-risk, such as during dispersal, migration or fledging (e.g. Figure 4.12).

Similar signalling principles to signage apply, with humans as the intended receivers and responders to the signal. Signals can be optimised to improve effectiveness and should be delivered reliably. A positive effect of smartphone applications as warning systems on driving behaviour has already been supported by several studies (e.g. Albert et al. 2016, Cardamone et al. 2016, Botzer et al. 2017). The German app 'Wildwarner' had over 50,000 registered users in 2021 and it warns drivers when they enter high-risk WVC areas based on information from citizens, previous WVCs sourced from police reports, and environmental conditions. In a survey of ninety-nine users of the app, 97% reported that they slowed down or drove more attentively after receiving a warning from the app (Trager et al. 2021).

In 2023, Volkswagen included an 'Animal on road' warning in their electric vehicle range, with other manufacturers likely to follow suit. It is unknown if this warning is from reported hazards in the area or via an on-board animal detection system.

The effectiveness of all in-vehicle warnings at reducing WVC has not been quantified, but is likely to help if the warning is associated with an observed animal on road, reinforcing that the risk is real.

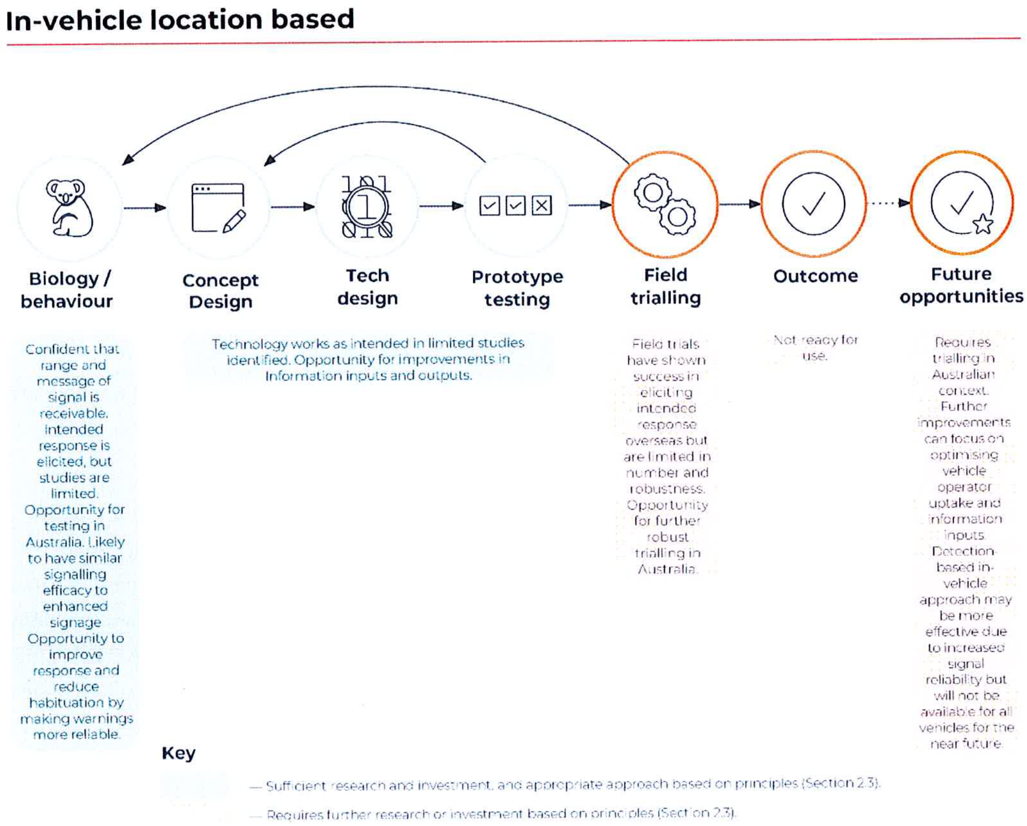

Figure 4.16 Qualitative assessment of in-vehicle location based applications at reducing rates of WVC and identification of areas for further research and development.

4.2.3 *Pre-vehicle signals*

Pre-vehicle signals are sent before the motorist or vehicle enters the high-risk area, usually days, weeks or months prior.

4.2.3.1 Education and awareness

Driver experience and awareness can influence the likelihood of a WVC. New drivers, or those unfamiliar with a specific road or WVC 'hot spot' areas, such as tourists, are more likely to be involved in collisions with animals than experienced or WVC-aware drivers (Bender 2003). Road safety education campaigns and publicly available information should aim to increase awareness of WVC risks and provide information on how to reduce the risk (Huijser et al. 2021). Beyond signs, common methods to distribute this information includes print media (newspapers, brochures, etc.), radio, TV, the internet and social media. Wildlife agencies, NGOs, and tourist visitors' centres can also support the dissemination of information, including with bumper stickers which declare "I brake for" specific species at risk of WVC.

While these approaches have wider applicability for many species and over a wide area, there is no guarantee the vehicle operator will receive and respond to this information. Furthermore, it is likely that only a limited subset of the community will respond accordingly to these education campaigns (Huijser et al. 2021). Strong beliefs and values are not easily swayed by education, and this information may not want to be received (Ramp et al. 2016). Acquiring knowledge also does not necessarily lead to behavioural change (Vanlaar et al. 2019).

Furthermore, there appears to be an overall apathy to roadkill in the general population and a hierarchy of concern for certain types of species – large, iconic or charismatic species tend to illicit greater levels of concern than smaller species, reptiles or invertebrates (Lunney 2013). Indeed, many motorists target certain ‘undesirable’ species and intentionally run them over (Beckmann and Shine 2012). Changing such entrenched behaviours will take time and education programs will need to focus on relevant levers and hooks for different types of people according to their values and beliefs (Lunney 2013).

An additional challenge is the lack of public understanding of how animal detection systems (ADS) operate (Gordon et al. 2004a, Smith et al. 2016, Grace et al. 2017). The effectiveness of ADS at reducing WVC is reliant on the response of vehicle operators and a targeted education and awareness program is essential to educate people on the appropriate response. A study of driver responses to taxidermised deer on roadsides in the USA in the 1970s had to be halted part-way through the experiment because 5 – 10 % of motorists responded dramatically to the presence of the deer, including sudden heavy braking and stopping on the road, increasing the risk of vehicle-vehicle collisions (Reed and Woodard 1981). Appropriate education will be needed to accompany any form of technological solution in order to elicit the most appropriate response from motorists.

Driver awareness campaigns must be widespread, ongoing and consistent across state boundaries to have maximum effect. They should also target different demographics (new drivers, old drivers, tourists etc), and include education programs that focus on specific high-risk areas – e.g. protected areas or national parks, as well as high-risk areas generally.

See Section 4.2.2.1 for more details on in-car apps and driver warning systems.

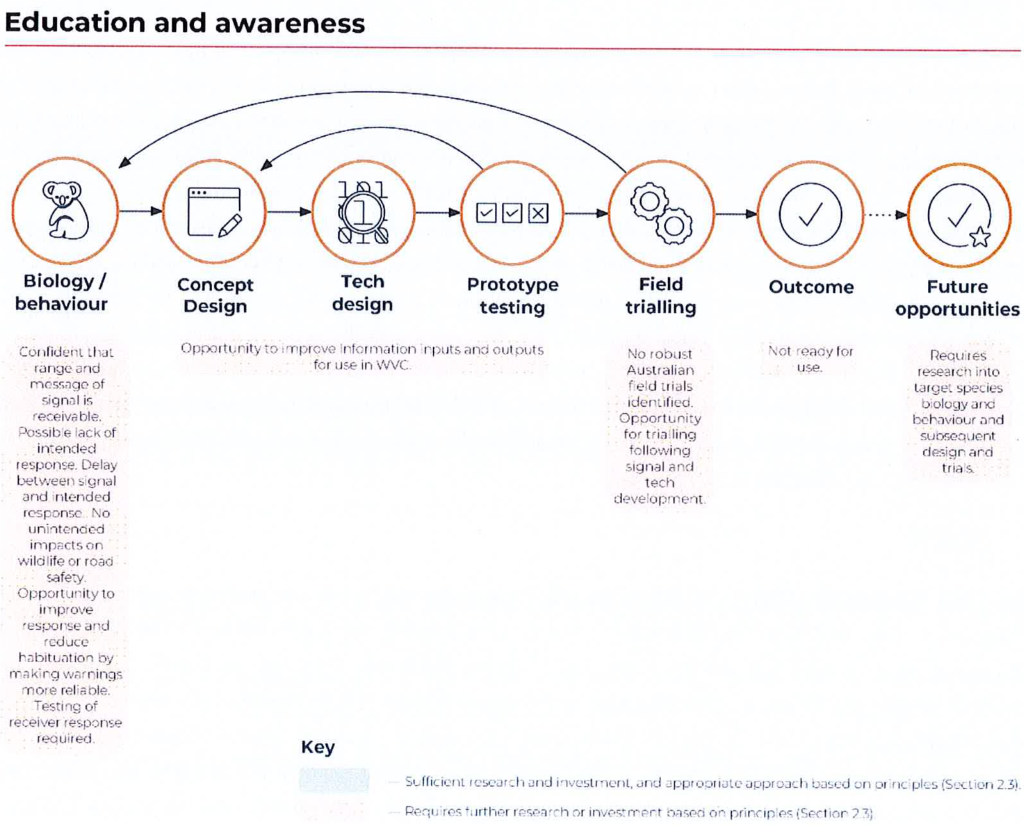

Figure 4.17 Qualitative assessment of driver awareness and education at reducing rates of WVC and identification of areas for further research and development.

5 Evaluation of signal-based approaches with animal and/or vehicle detection systems

5.1 Animal detection and identification systems

The ability to rapidly and accurately detect and identify wildlife on or near roads and railways is critically important to the development and adoption of effective technological solutions to WVC (Grumert and Nusia 2023). This section summarises some of the common and emerging technology types that are utilised for wildlife detection and identification. Note that these technologies do not reduce WVC per se, but are used in combination with other equipment and systems that have been specifically designed to mitigate WVC, which are described in Section 5.2 and 5.3. Multiple detection types can be combined, and this approach may allow detection types to complement each other, for example, where camera systems may be unsuitable at night, and thermal systems unsuitable during the day, both approaches can be implemented together so that the system is suitable across the full daily cycle. The suitability of detection types is likely to vary among target species, climates, locations etc, and should be considered and tested in the specific context they will be used in prior to wide-spread implementation.

5.1.1 Radar

Radio Detection and Ranging (Radar) is an active sensing technology that uses long-wavelength electromagnetic waves, typically between 20-300 gigahertz (GHz), to determine the distance, direction and velocity of objects relative to the site. Using the angles of the emitted wavelengths and the time between the emission and detection, a 3D image of the surrounding environment can be calculated. Unlike some other forms of technology, radar continues to work in challenging conditions that may increase the risk of WVC, such as heavy rain, fog, snow and complete darkness (Viani et al. 2016). Examples of wildlife detection devices that utilise this technology include cameras and enhanced speed signs designed to reduce vehicle speeds in high collision-risk areas. An example of radar detection used in intelligent signage comes from Viani et al. (2016), who placed 'nodes' along a section of roadway in Italy known for deer crossings, comprising relatively inexpensive doppler radar modules to detect deer near the sensors and wirelessly connected to a driver warning system. The radars correctly detected deer about 63% of the time, although also produced some false negatives (~13.5% of detections). A review of a radar-based animal detection and driver warning signage systems for large mammals in the USA found that it performed reasonably well, with animals detected sufficiently early to warn drivers 58 – 85 % of the time (Huijser et al. 2017).

5.1.2 LiDAR

Light Detection and Ranging (LiDAR) is an active sensing technology that works by emitting laser pulses or infrared light in the frequency range of 850 to 940 nanometres (nm) and measuring the time it takes for the light to travel back to the source. Pulses of light can be emitted from a range of different platforms, including airplanes, helicopters and ground-based stationary or mobile platforms, at sampling rates exceeding 150 khz (150,000 pulses per second). This data is then used to generate highly accurate (10 – 20 cm) 3-dimensional information about the area of interest, which includes various environmental or topographical features. LiDAR can be used during the day and at night, and offers higher resolution and accuracy compared to radar but is more expensive. LiDAR relies on the light being bounced back to the sensor, and thus is unable to see past the first object.

LiDAR technology is currently used in transport systems to detect intruders and other obstacles on railway tracks. These units can be mounted on the side of the railway or at the front of trains, providing real-time notification to train drivers of potentially dangerous track conditions ahead. The trackside system is currently focussed on detecting landslides in specific areas prone to landslides, as well as people and other intruders in at-risk areas of track. The train-mounted

LiDAR system is being used in China and can reportedly function on trains travelling up to 300 – 350 km hr^{-1} (LSLiDAR | Railway Intrusion Monitor System Ensures Rail Traffic Safety - Leishen Intelligent System).

We are not aware of LiDAR being used to detect wildlife and provide a system to avoid or reduce rates of WVC, however the system has the capability to do that.

5.1.3 Break-the-beam sensors

Break-the beam sensors consist of an emitter projecting a beam of infrared light, laser beam or microwave radio signal to a receiver (Nandutu et al. 2022b). Animals are detected when they move through and 'break' the infrared beam of light (Grumert and Nusia 2023), subsequently triggering an action like activating a warning sign to notify vehicle operators. Break-the-beam sensors are most effective for large-bodied animals that 'walk' through the beam and are less effective for smaller animals and those that may hop or jump above the beam.

Some limitations of the technology include the need for more senders and receivers of the beam in locations that are curved, sloped or are within vegetated landscapes because these landscape features interfere with the beam (Nandutu et al. 2022a). Break-the-beam sensors are also prone to false positives because the sender and receiver can be easily mis-aligned and every break in the beam is interpreted as a wildlife movement. Break-the-beam sensor technology can be coupled with camera systems to identify the cause of the broken beam and minimise false-positives, as well as monitor animal movements or use of wildlife crossings (Gužvica et al. 2014). Integration of advanced machine learning algorithms of the images (Section 5.1.9) would help to make the system intelligent, greatly improve its accuracy, and help to eliminate false positives (Nandutu et al. 2022a).

5.1.4 Passive Infrared (PIR) motion sensors

A commonly used form of technology, Passive Infrared (PIR) sensors detect thermal energy radiation emitted from the surface of objects. The sensor is triggered when an animal enters the field of view, causing a difference in temperature between its surface temperature and the surface temperature of the background environment (Welbourne et al. 2016). Given that the technology is relatively cheap and requires a low energy source, PIR motion sensors are commonly used in surveillance cameras and wildlife camera traps. However, like all technology, it has some limitations. For example, animals may not be detected if they have a similar temperature to the background environment (Welbourne et al. 2016). There can also be high rates of false-positives due to vegetation intrusion and sensors failing to differentiate between hot air and body heat of animals (Smith et al. 2016, Grace et al. 2017, Nandutu et al. 2022a). High variability in the environmental temperature and high winds can also result in false triggers (Jacobs and Ausband 2018).

AI and machine learning (Section 5.1.9) are increasingly being used to identify the animals caught on cameras that are triggered using PIR (Tabak et al. 2019, Willi et al. 2019, Vélez et al. 2023). If the image analysis is quick enough, it can be used to detect wildlife in near-real time. A key limitation in the application of PIR sensors is the distance over which animals can be detected (typically up to approximately 50 m) and issues with false triggers due to variability and/or lack of difference in the heat signature of animals and the background ambient environment.

5.1.5 Animal-borne tags

For over four decades animal-borne tags have been used to record information about animal movement, behaviour and their environment and include radio-tracking, GPS tracking and satellite tracking. The animal-borne tag can emit a signal which is received by an external receiver (e.g. proximity tag, VHF radiotransmitter) or it can perform 2-way communications (e.g. GPS or satellite tracker). The technology has developed over the years and become extremely sophisticated, recording data from multiple sensors at high frequencies for long periods of time (Holton et al. 2021). Technological advancements have also reduced the size of animal-borne tags, increasing their use on a range of smaller species.

Animal-borne tags can potentially contribute to reduced rates of WVC by providing real-time information about animal locations to alert vehicle operators of their proximity to a danger zone, such as a road or railway. Similar technology can also be used to keep animals away from danger zones via geofencing (Section 5.2.1.2), in which tags or collars emit an aversive sound or electrical shock to discourage animals from entering these areas. However fixing animal-borne tags to animals is intrusive, labour intensive, costly and can raise animal welfare concerns (Xing et al. 2022). In addition, the risk of non-tagged animals entering the danger zone and not triggering a warning for motorists or animals may present an unacceptable risk of WVC if motorists are expecting wildlife to be excluded. Animal-borne tags are probably most suited to high profile at-risk species in restricted locations where a known population occurs, and this approach is unlikely to be feasible for widespread species.

5.1.6 *Optical and thermal cameras*

Optical cameras are passive devices, meaning they collect ambient light to form images and have long been used to monitor the presence of wildlife at particular locations. However their reliance on ambient light to function limits their use in the dark. In contrast, thermal cameras can be used at night as they use the heat signature of objects to create an image (Section 5.1.4). Optical and thermal cameras can be mounted to the front of vehicles or be installed on the side of roads or railways and generally require an uninterrupted line of sight to be maximally effective. Thermal cameras can have a range of up to approximately 1 km or potentially longer depending on the size of the target species. Optical and thermal cameras can take still images or video footage.

Cameras can be combined with other forms of technology, such as AI powered approaches to identify objects in the photo (Section 5.1.9). For example, AI was recently used to undertake image analysis of video forage of koalas in an effort to understand their road crossing behaviour and to activate intelligent signage (Xing et al. 2022). The combined use of camera and AI technology enabled more accurate and rapid detection of koalas in their environment, information which can be used to help design and optimise the location of fauna mitigation measures on roads for this species.

A similar trial is underway using dashcam footage to detect and identify turtles on roads in NSW with Western Sydney University and TfNSW (1 Million Turtles). The project has completed proof of concept trials which indicate a 90% success rate in detecting and correctly identify turtles on the road while driving at 80kmhr^{-1}. The results will be used to identify hotspot areas on existing roads where turtles are crossing roads as well as inform locations where mitigation measures should be prioritised for retrofitting to existing roads (R. Spencer, unpub. data).

5.1.7 *Acoustic sensors*

Acoustic sensors detect specie-specific sounds made by animals, typically their calls when they communicate to each other. Depending on the animal, sounds can span a wide range of frequency bands, including infrasound (below 20 Hz, e.g. elephants), the human audible range (20 Hz to 20 kHz), and ultrasound (above 20 kHz, e.g. insectivorous bats). A notable advantage of acoustic sensors is their ability to detect animals even when they are obscured by objects such as trees or other structures or not visible due to cloud, rain, light levels, etc. However, a significant disadvantage using acoustic sensors to reduce WVC is that the detection is only possible if the target animal makes a characteristic sound at the time when they are approaching or crossing the road or railway, and that the sound is detected by the recorder. Additionally, detecting animals near loud environmental noises, such as busy streets or heavy rain, can be challenging. The latest advancement in acoustic technology is to couple acoustic recorders with AI to identify animals based on their sounds.

We are not aware of acoustic sensors being used to detect wildlife and provide a system to avoid or reduce rates of WVC, however the system has the potential capability to do that.

5.1.8 *Seismic sensors*

Seismic sensors measure environmental vibrations such as those caused by the footsteps of large animals. By analysing these signals, it is possible to identify animals based on the strength, frequency distribution, and duration of the vibrations, as well as potentially the distance from the recorder. Since seismic sensors do not rely on a field of view, they can detect animals behind objects like trees. However, the propagation of vibrations is highly dependent on ground conditions (e.g. hard stones, sand, mud), making generalisation of these sensors challenging in different conditions and times of year. This technology is also less useful for smaller terrestrial animals which may go undetected by seismic sensors and not suitable for species that fly or live in trees.

An example of a seismic sensor is Perimtrax, a buried cable capable of detecting electromagnetic field disturbances. Druta and Alden (2019) tested this device along with an intelligent signage system in the USA during an 11-month trial. The sensor detected mid and large-bodied animals such as deer and coyote with 99% accuracy. Approximately 80% of drivers either braked or slowed in response to the connected intelligent sign. Another trial of seismic sensors in the USA, found that they were more effective at avoiding false triggers compared to laser tripwires (Wood 2013).

5.1.9 Artificial intelligence and machine learning

All animal and vehicle detection systems require an intermediate step to convert the data collected by the detector into usable information, such as confirmation of the presence of wildlife which informs the risk of WVC. For example, photos require analysis to confirm if the camera was triggered by an animal, and if the animal is likely to cause a WVC. This information can then be used to activate an intelligent sign or other warning system.

Data from detectors also need to be interrogated to provide automated vehicles with the necessary information to respond appropriately. For example, the automated response of a vehicle to a small amphibian or large mammal on the road should be different. Ideally, the detection system and data analysis should be capable of determining species, the location of the animal (e.g. in middle, edge or verge of road), and whether it was moving towards or away from the vehicle – information which informs the response of the vehicle.

Historically, data from detection systems was analysed and interpreted manually before it could be used, however the development of machine learning and other algorithms such as deep learning and convolutional neural networks to analyse the data have increased the speed at which this can be undertaken. As algorithms improve, and accuracy of the analysed data increases, the computer-aided identifications can be more accurate and completed more quickly than manual processes.

AI and machine learning are tools that inform and support the decision-making process and can activate intelligent warning signs, in-car warnings, automated vehicle responses and animal deterrents. These systems will become faster and more accurate as the detection systems and algorithms become more sophisticated, increasing the real-time benefits of these technological solutions.

5.2 Targeting wildlife

5.2.1 Wayside deterrents

Wayside signal-based approaches that target wildlife are installed on the verges of roads and railways and produce signals that are intended to warn animals to not enter the road or railway or deter animals and encourage them to leave the road or railway. Typical examples include more advanced forms of roadside reflectors (Section 4.1.1.1) which are dynamic light and sound deterrents that are triggered when vehicles approach and therefore permit the free movement of wildlife movement in the absence of traffic (Appleby and Jones 2020, Reeves et al 2022).

5.2.1.1 Wayside deterrents with detection

Virtual fences are an example of a vehicle-activated roadside deterrent that aims to modify the behaviour of wildlife. Virtual fences in this context are different to geographic virtual fences (Section 5.2.1.2). Originally developed in Austria to prevent WVC with deer, virtual fences are small electronic devices that are mounted on posts at regular intervals on alternate sides of the road. Devices are activated by approaching vehicle headlights and, when triggered, they emit sound and light stimuli that are intended to alert animals that a vehicle is approaching, theoretically encouraging them to leave the roadside (Fox et al. 2018). Similar devices for railways have been trialled in Europe along railways to deter roe deer (Babińska-Werka et al. 2015)

The first installation and trial of virtual fences in Australia was conducted in north-west Tasmania in 2014, where roadkill was recorded using identical methods for four months before installation of the fence and for three years after installation (Fox et al. 2018). The study reported a 50% reduction in rates of roadkill of some abundant species, such as

Tasmanian pademelons and Bennett's wallabies. The study was subsequently critiqued, with criticisms of the light and acoustic stimuli used and numerous flaws in the experimental design of the study, including imprecise measurements, confounding effects, low statistical power, and failure to consider habituation (Coulson and Bender 2019).

Numerous trials have since been undertaken to further measure the effectiveness of virtual fences, including elsewhere in Tasmania (Englefield et al. 2019), on Bruny Island (Candy et al. 2024), south east Queensland (Reeves et al. 2021), semi-rural NSW (Stannard et al. 2021) and the residential-rural landscape on Phillip Island, Victoria (C. Connelly, unpub. data).

A study on the effectiveness of virtual fences on wombat roadkill was conducted along a 100 $kmhr^{-1}$ section of the Old Bega Road, in SE NSW (Stannard et al. 2021). Fewer wombats were killed in the 'fenced' than 'unfenced' area after installation (23 individuals and 6 individuals, respectively), however a similarly large reduction in wombat roadkill was observed at a nearby 'unfenced' control road (64 to 17 individuals, respectively). The study concluded that virtual fences may aid in reducing rates of wombat roadkill, but further research is required. The study was subsequently criticised by both Candy and Englefield (2022) and Coulson and Bender (2022), who both argued the experimental study design was insufficient to detect a measurable effect.

Two recent studies of virtual fences in Tasmania, which included a robust crossover and repeated before-after-control-impact experimental designs, as well as extended monitoring (in the case of Candy et al. 2024), both failed to detect a significant effect of the fence on rates of roadkill of Tasmanian pademelons, Bennett's wallabies or common brushtail possums (Englefield et al. 2019, Candy et al. 2024). The 2019 trial was conducted on a three-lane single carriageway highway, with a posted speed limit of 100 km hr^{-1} and the Bruny Island trial was 2-lane unsealed road with a speed limit of 80 km hr^{-1}. At best, the studies concluded that the fences are likely to lead to, if anything, only a minor reduction in roadkill. A recent study conducted on Phillip Island in Victoria also failed to detect any significant reduction in rates of WVC on swamp wallabies and common brushtail possums (C. Connelly et al, unpub. data.). Interestingly, a recent study on the south coast of Victoria found no detectable impact of ultrasonic devices at deterring foxes and protecting nesting shorebirds (Saurine et al. 2024).

Despite these studies failing to show a significant effect, and that other studies were heavily criticised, virtual fences have been installed at many locations across Australia (Wildlife Safety Solutions, 2024), often with reportedly high success rates. However, none of these 'success' stories are accompanied by evidence or robust study designs to enable independent verification of the results. We contacted the managers (primarily local councils) of roads where virtual fences have been installed and requested information about the degree of effectiveness. Most of the councils who responded lacked scientifically robust data on rates of WVC and roadkill to support the claims of effectiveness.

Virtual fences are appealing because:

- Compared to wildlife crossing structures and physical fencing, they are extremely cheap to purchase and install.
- They require little maintenance.
- They do not emit noise or light in the absence of vehicles or during the day, thus not affecting animal movement at these times.

Some of the limitations associated with virtual fences are similar to those identified for reflectors:

- Approaching vehicles must activate the stimuli with sufficient time before arriving at that location to theoretically provide enough time for an appropriate response by the wildlife.
- Fauna must hear or see the stimuli amongst all the other noise and disturbance of the road or railway.
- Fauna must associate the stimuli with the danger of an oncoming vehicle and respond appropriately (i.e. leave the road via the most direct route and not move in front of approaching vehicles).
- If the stimuli are not associated with danger, it must cause sufficient pain or distress to cause the animal to move away.
- Fauna must not habituate to the stimuli over time.

— There is limited understanding of the most effective visual and acoustic stimuli for different species of Australian fauna.

There is potential for further development and refinement of the virtual fence approach, but further research must consider:

— Effectiveness on roads and railways, under different road (road type, number of lanes), traffic (volume and speed), weather and landscape (e.g. rural, urban-rural fringe, bushland) conditions.

— Acoustics and visual variations specific to each targeted species.

— The distance from the fence that animals detect the signal.

— The response of animals to the signals.

Trials of wayside deterrents on railways in Canada and Europe suggest that acoustic deterrents can be effective if they consider the biological relevance of the warning signal. A prototype of a deterrent was tested in an area with high rates of collisions between trains and grizzly bears in Banff and Yoho National Parks in Canada in 2015 – 2016 (Backs et al. 2017). The deterrent was triggered by an approaching train, and various train detection methods were tested, ensuring animals up to 200 m away were forewarned of the approaching train. The prototype (Figure 5.1) was then tested in-situ in 2016 – 2017 to provide warning to wildlife 30 seconds before the train passed locations grizzly bears, brown bears, coyotes and deer were frequently encountered on the tracks (Backs et al. 2020). The warning signals, consisting of flashing lights and bells, triggered flight initiation of large mammals up to 62% earlier and smaller animals 29% earlier than in the absence of warning signals. These results indicate that warning systems applied ahead of train arrival can initiate flight sooner than without them and may reduce rates of wildlife-train collisions (Backs et al. 2020).

A study of electronic devices emitting natural warning calls of birds, predators and ungulates installed on two sections of railway track in Poland concluded that animals reacted 20 seconds faster when the devices were operational and the percentage of roe deer which successfully left the track was 84% vs 68% (Babińska-Werka et al. 2015). No evidence of habituation over the four-year study was observed. The study included an on-off-on cycle at one location and a 'permanently on' deployment at the second study site, however no controls or replication of treatments were utilised, limiting the broadscale generalisations of the results (Babińska-Werka et al. 2015)

Further trials are currently being undertaken in Scandinavia and elsewhere in Europe, with a range of auditory deterrents (e.g. human voice, predator calls, beeps and whistles) and train detection systems. Most deterrent systems are currently trackside mounted, with a few being mounted to the front of trains. A promising approach, currently being tested in Sweden, involves the use of pre-recorded human voices that are emitted only when an animal and a train are detected, minimising the risk of habituation. Important aspects of the trials include scientifically robust study designs (data collected before and after at control and impact sites), evaluation of animal responses and behaviour as well as consideration of habituation (A. Seiler, unpub. data).

These international trials of wayside deterrents indicate potential suitability of this approach to Australian conditions if the stimuli are developed and specifically tested on Australian fauna and if the stimuli can be deployed well before the arrival of vehicles. Railways may be more suited to wayside deterrents than roads because there are typically fewer train movements than vehicles on roads, minimising the likelihood of habituation. In addition, train movements are more predictable and currently able to trigger responses well-ahead of the moving train.

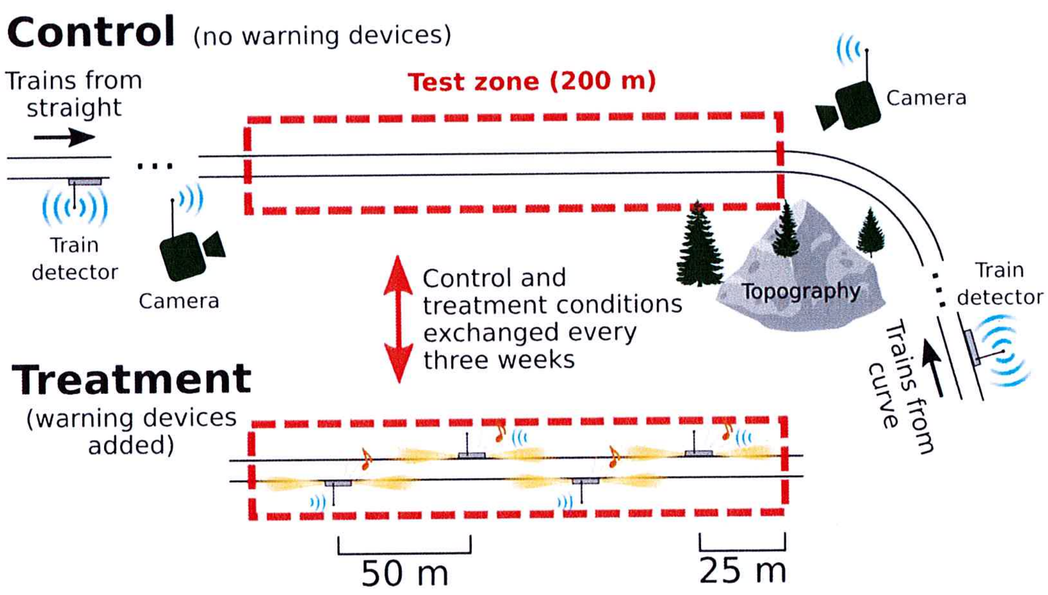

Figure 5.1. Design of experimental tests of fauna deterrents triggered by passing trains in Banff National Park, Canada. When a train passed the train detector, a wireless signal was transmitted to active cameras that recorded the presence and responses of wildlife. Source: (Backs et al. 2020)

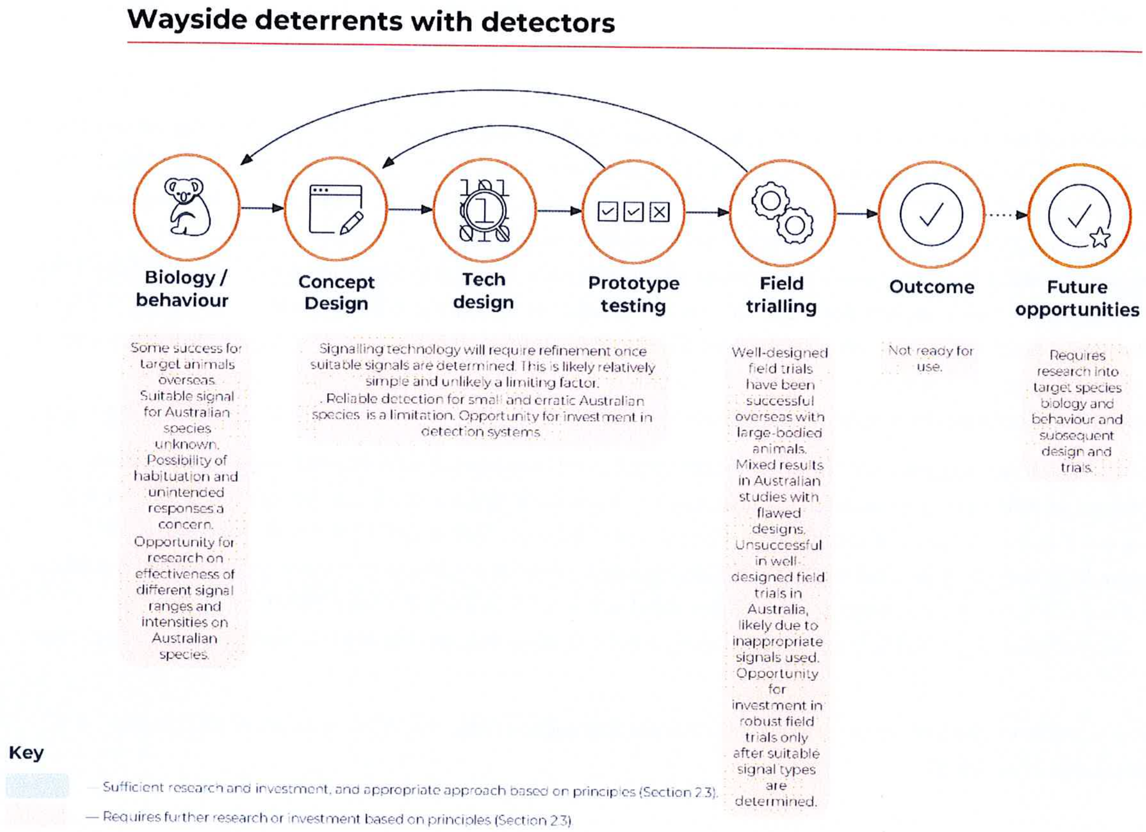

Figure 5.2 Qualitative assessment of dynamic light and sound deterrents at reducing rates of WVC and identification of areas for further research and development.

5.2.1.2 Geofencing - location-activated animal-borne signals

Whilst similar to virtual fences (Section 5.2.1.1), geographic virtual fences (hereafter called geofences) utilise a combination of animal-borne tags, typically deterrent collars, and wireless systems to control the movement of wildlife within a pre-defined boundary. Geofences typically trigger a response from the animal by alerting them when they approach or cross a pre-defined boundary.

The concept was originally developed to confine livestock to areas without requiring physical fences. Outside of the agricultural industry, the technology was reportedly first used in 1976 on captive coyotes to teach avoidance of prey (Linhart et al. 1976). It works by defining a virtually fenced area and uploading these boundaries onto an animal-borne device (e.g. a tracking collar). These devices are then deployed on target animals which continuously monitors their position in relation to GPS defined boundaries. When the animal strays out of the GPS defined zone, an alarm system is triggered. This usually involves the delivery of an auditory warning followed by electric stimuli to the animal wearing the collar to discourage them from moving further (Datta et al. 2016, Cabral de Mel et al. 2022).

Geofence responses could also be used to activate intelligent signs along roads or railways (Section 5.3.1.1) and inform vehicle operators about the approaching danger (Datta et al. 2016). The fact that it is the animal's movements triggering the alarm system is a key difference between this technology and standard virtual fences.

Geofences with deterrent collars share many of the same benefits as standard virtual fencing in that they are flexible, relatively cost-effective and able to implement over larger areas (Datta et al. 2016). Some additional benefits that this system affords include the temporal and spatial flexibility to alter the boundaries as required, and that the alarm systems are only triggered when collared animals have crossed a defined boundary, and not whenever vehicles are passing.

Furthermore, this technology allows for real-time, continuous and accurate location tracking of individual animals which can provide useful data and increase scientific knowledge on animal movement patters and distributions (Cabral de Mel et al. 2022).

Challenges with this technology include the labour intensiveness of fitting the target individuals with collars, and any associated negative effects that this might have on the individual such as skin necrosis or irritation from the collar (Cabral de Mel et al. 2022). There is also a requirement for the collar to have a long-battery life or solar recharging capacity to provide real-time positioning information and to generate sounds and/or electric shocks. Real-time monitoring also requires uninterrupted satellite and mobile network communication, which may not always be available in remote areas (Cabral de Mel et al. 2022). It is also possible that some species may not respond to the sound and/or electric stimuli the same way livestock do, which could render the technology ineffective at mitigating WVC (Cabral de Mel et al. 2022). Lastly, unlike standard virtual fencing which allows wildlife to freely move in the absence of vehicles, geofences have a pre-defined boundary that discourages the movement of animals regardless of vehicle presence. Therefore this technology has greater potential to fragment populations and disrupt the distribution of individuals across the landscape.

Such technology is unlikely to prove useful for abundant species with widespread distributions, such as kangaroos. Instead, geofences and deterrent collars are most effective when trying to target a small number of high profile or high value species, or in an isolated area of significance. For example Endeavor Veterinary Ecology in Queensland are currently researching the use of geofencing to pre-define high-risk zones and subsequently issue an alert when a koala is in or approaching danger such as a construction site or road (Endeavor Veterinary Ecology 2024). Overseas, the technology has also been suggested for use on Asian elephants to mitigate human-elephant conflict (Cabral de Mel et al. 2022).

Further research and development on the effectiveness of this approach at reducing WVC is required (Rajalashmi et al. 2021, Cabral de Mel et al. 2022).

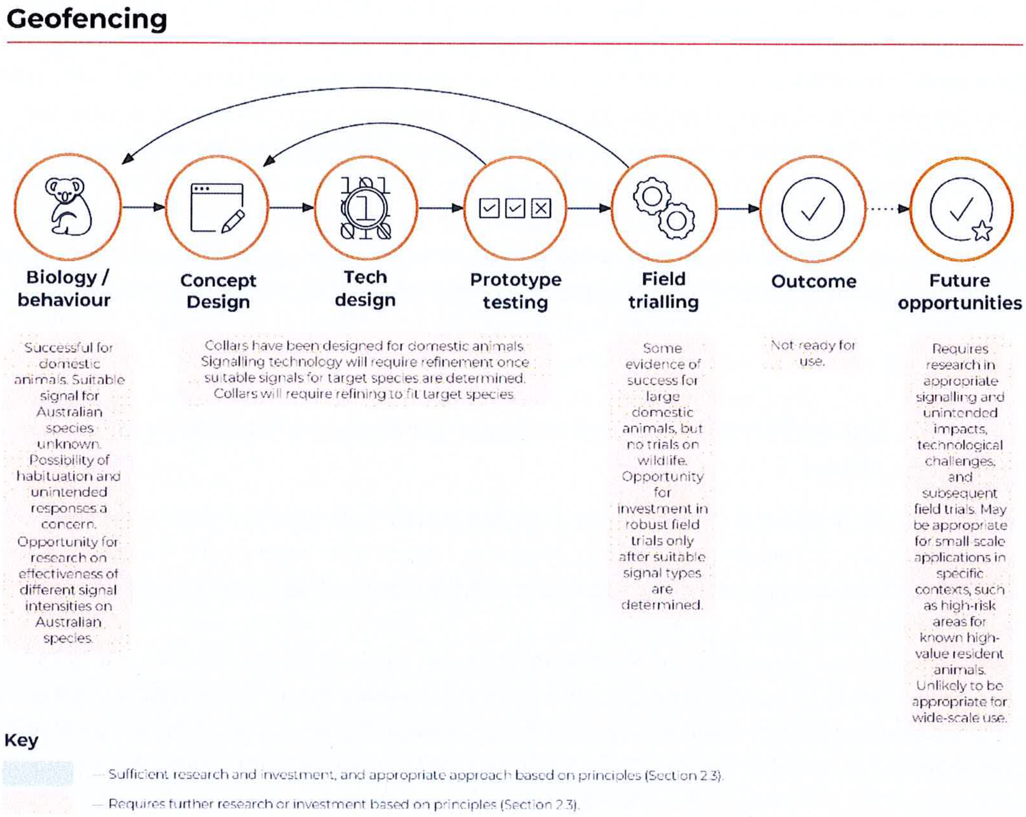

Figure 5.3 Qualitative assessment of geographic fencing with deterrent collars at reducing rates of WVC and identification of areas for further research and development.

5.2.2 *Vehicle-borne deterrents triggered by detection systems*

Vehicle-borne deterrents that also deter wildlife are similar to simple vehicle-borne deterrents (Section 4.1.2) except they are triggered by an animal detection system. This setup allows the deterrent to be more selective, for example, only activating when an animal is detected, or possibly selecting deterrent signals based on which animal is detected.

We are unaware of any vehicle-borne detection-based deterrent systems that have been developed or trialled. This solution could be more effective at reducing WVC and disturbance to roadside habitat than vehicle-borne deterrents alone. Research should focus on appropriate signals for target species, as well as in-vehicle detection systems to develop this solution further.

5.3 Targeting vehicle operators

5.3.1 *Wayside signals*

5.3.1.1 Intelligent signage

Intelligent signs are dynamic wildlife warning signs that are connected to animal detection systems (ADS) (Section 5.1). Intelligent signs are often used as a stand-alone measure or in combination with at-grade crossings (Section 6.1). Animal detection systems detect wildlife and sends a signal to activate a sign to warn drivers about nearby fauna and reduce speed accordingly. When no animals are detected, the sign remains inactive.

In contrast to static or enhanced signs (Section 4.2.1.1 and 4.2.1.2), intelligent signage has the potential to accurately inform drivers, in real time, whether wildlife are detected on the roadside or railway verge. Whilst static and enhanced signs are most effective when strategically placed at WVC hotspots and activated at certain times, detection systems enable intelligent signs to be effective everywhere it is installed, so long as the activated warning signs are visible to vehicle operators (Huijser & McGowen 2010). The effectiveness of intelligent signs varies across weather and geographical contexts and is most effective when accompanied with mandatory speed reduction (Huijser et al. 2009). A driving simulator study found that intelligent signage resulted in significantly lower crash probabilities because participants reduced their speed and braked earlier in response to animals on the road (Grace et al. 2015). In addition, it found this significant effect with both text and picture-based signs, though it was slightly stronger for picture-based warnings, especially at night. A 10-month trial evaluating driver responses to intelligent signage in northern California found that when active, the signs reduced traffic speed by an average of 5 - 8 kmh^{-1} (Nowakowski et al. 2013). A 2-week trial of intelligent signage at a WVC hotspot on a rural highway in England found a statistically significant reduction in from 106 $km\ hr^{-1}$ to 89 $km\ hr^{-1}$, when signs were active (Mukherjee et al. 2013). Intelligent signage in Wyoming USA reduced vehicle speed at night by 6% (6 $km\ hr^{-1}$), which increased to 20% reductions when the sign was paired with a deer decoy (Gordon et al. 2004b).

For intelligent signage to be an effective WVC mitigation measure, consideration must be given to the spacing of signs and their proximity to the area of concern, ensuring enough time to respond appropriately when the sign is activated (Huijser et al. 2015). As for static signs, the main determinant of effectiveness of intelligent signs is driver response, which is influenced by their trust in the sign (Huijser et al. 2015). Therefore, the ADS must reliably detect fauna that approach the road and yield few false-positive detections, otherwise drivers lose confidence in the system and ignore them. Similarly, given a history of technical issues in older applications (Huijser et al. 2009), regular maintenance is required. Design and placement of intelligent signage should also consider the risk of distracting drivers or overloading them with information. Signs should be simple, quick to read, and used sparingly and efficiently. A review of an intelligent signage system for large mammals in the USA found that it detected animals sufficiently early to warn drivers 58 – 85 % of the time (Huijser et al. 2017).

A recent literature review by Nandutu et al. (2022a) of sensor technologies used in WVC mitigation measures concluded that many ADS have not incorporated state-of-the-art approaches or technologies to improve detection accuracy and delays. For example, ADS efficiency would be improved by using relevant WVC datasets and advanced machine learning algorithms to minimise false positives and increase analysis speed and triggering of signs and other subsequent actions (e.g. in-vehicle warnings – Section 5.3.2).

Further research is recommended to improve ADS because they remain unreliable for detecting Australian wildlife and more generally for small- and medium-sized fauna which are often subjected to higher rates of WVC than larger fauna (Huijser and McGowen (2010); Nandutu et al. (2022a)). Further research is also recommended to investigate if changes to driver behaviour correlate with reduced WVC rates. A study by Dai et al. (2009) in the USA found that while intelligent signage appeared to alter driver behaviour, it did not result in a statistically significant reduction in WVC over the two-year study period. The authors recommended further studies integrating lessons learned from the pilot study, including updates to detector and signal types and improvement of study methodologies.

Trials are currently underway in Queensland to use ADS to detect cassowaries on roads and roadside verges and trigger intelligent signs to warn motorists of the increased risk of WVC with the species (Kunming et al., unpub. data). The signs were designed with input from focus groups and the effectiveness at triggering a response from drivers was tested using a driving simulator. Field trials are currently underway and no results are available as yet.

Intelligent signage can be improved using state of the art animal detection systems and artificial intelligence and machine learning to analyse the data received and create information to activate the intelligent sign. An example of this approach is given in Section 6.2.

Photo 5.1 An intelligent sign that is activated when deer (left) or southern cassowaries (right) are detected on the road. Source: (Dai et al. 2009) and Mao Shan, University of Sydney.

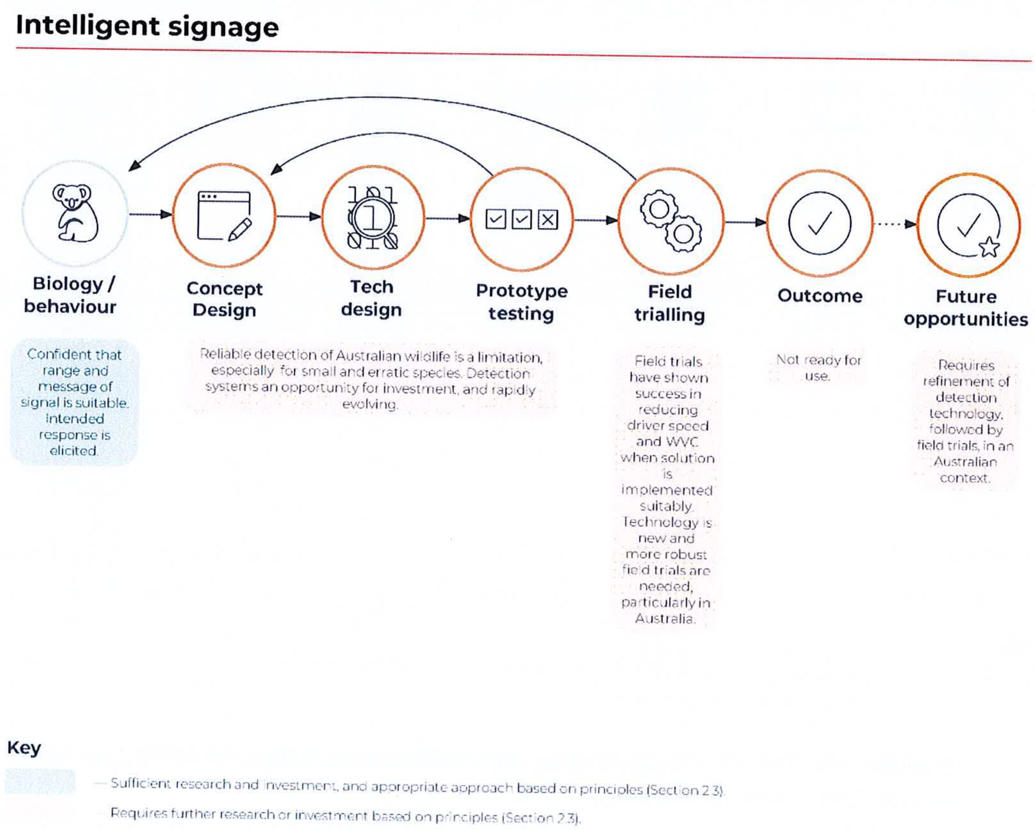

Figure 5.4 Qualitative assessment of intelligent signage at reducing rates of WVC and identification of areas for further research and development.

5.3.1.2 Activated wayside lighting

Lighting along roads and railways that turns on when animals and vehicles are simultaneously present and detected may potentially serve multiple functions:

— Increase the visibility and detectability of wildlife to motorists, thereby giving vehicle operators more time to respond.

— Warn wildlife of approaching vehicles and give them more time to respond and move away from the road or railway.

— Increase the detectability of vehicles to wildlife.

Many of the limitations associated with wayside lighting (Section 4.2.1.3) also apply to activated wayside lighting.

We are not aware of any activated wayside lighting along roads or railways that has been implemented to reduce the rate and severity of WVC.

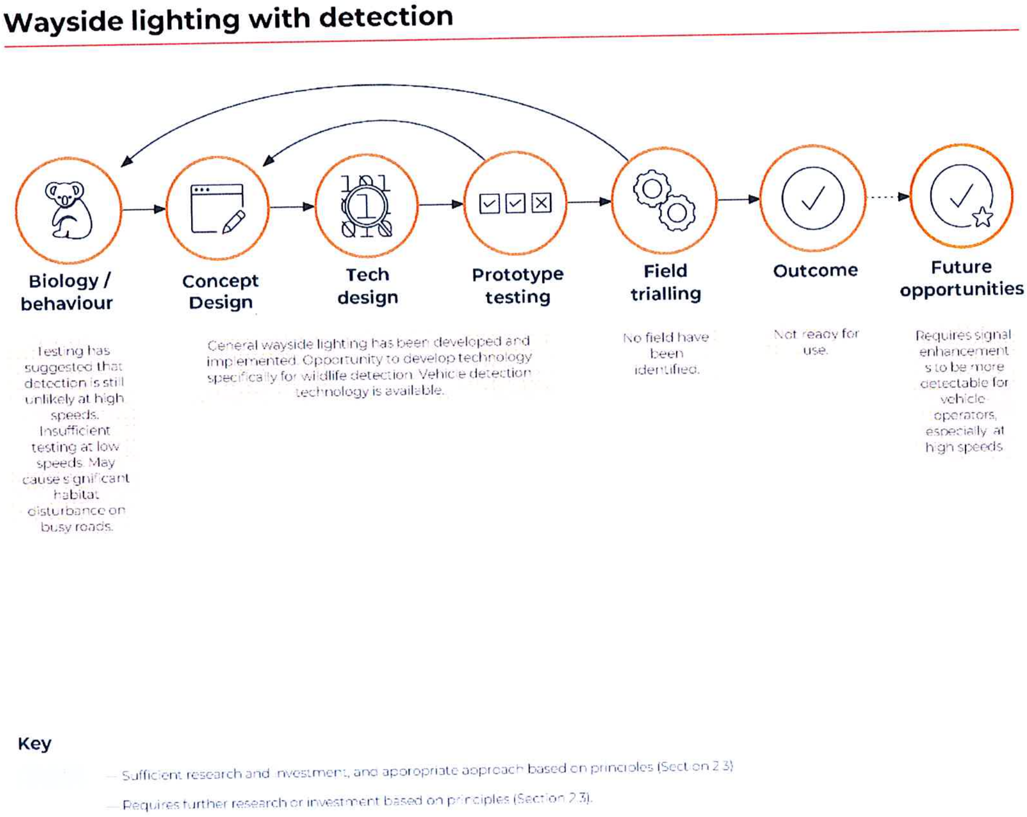

Figure 5.5 Qualitative assessment of wayside lighting with detection at reducing rates of WVC and identification of areas for further research and development.

5.3.2 *In-vehicle signals with animal detection systems*

In-vehicle signals are delivered to motorists via alerts inside the vehicles. These in-vehicle alerts are sent when an animal is detected by a vehicle- or wayside-mounted ADS, or by nearby connected vehicles.

In-vehicle signals that are activated by animal detection systems are intended to warn motorists in real-time of the presence of wildlife and utilises similar principles to signage. These signals have the same benefits as non-detector signals, with the additional benefit of higher reliability and wider functionality, as well as additional wildlife monitoring opportunities. Warning signals can trigger an appropriate response from vehicle operators when the signals are reliable (Section 4.2.2).

The signals can be targeted at vehicle operators, the operating system of autonomous vehicles, or both. For example, signals can warn the driver to the presence of animals as well as activate assisted braking. Computer-based vehicle automations already exist and are effective for uses such as pedestrian and vehicle collision avoidance (Rosén et al. 2010, Cicchino 2017).

A limitation in Australia for this solution is the capability of the system to detect hopping and erratically moving wildlife such as kangaroos. However, technology in this space has been rapidly evolving, and achieving this accuracy is likely. Investment in in-vehicle detection systems is a high priority to progress this solution type. This approach requires cooperation and collaboration between fields including ecology, technology innovation, and car production companies to achieve ANCAP (Australasian New Car Assessment Program) safety ratings and gain market share.

An Australian example of in-vehicle signalling and detection is the TurtleSAT smart phone application (R. Spencer et al., unpub. data). This app uses citizen science data to identify and notify users of high-risk areas for turtles crossing roads and to implement enhanced signage. The system has potential for real-time warnings as recent proof-of-concept trials using AI to detect turtles from car dash cameras showed a 90% success rate while driving at 80 km hr^{-1} (R. Spencer et al., unpub.). Vehicle-mounted cameras in Texas, USA were consistently faster and more accurate than traditional survey methods for small to large animals at speeds of 50 – 60 km hr^{-1} (Livingston 2019). Trials using vehicle-mounted cameras in Portugal were capable of accurately identifying amphibian and reptile roadkill when driving at 30 km hr^{-1} and further trials recommended (Lopes et al. 2016). While these examples prove animals can be detected from moving vehicles, further developments are needed to detect living animals at high speed and inform vehicle operators.

In 2023, Volkswagen included an 'Animal on road' information alert in their electric vehicle range, with other automated functionality planned for the years ahead (Figure 5.6). The effectiveness of these warnings at reducing WVC has not been quantified but is likely to be effective if the warning is associated with an observed animal on road, reinforcing that the risk is real. This work is being advanced by the C-ROADS Platform, a joint initiative of European Member States and road operators for the deployment of Cooperative Intelligent Transport Systems (C-ITS).

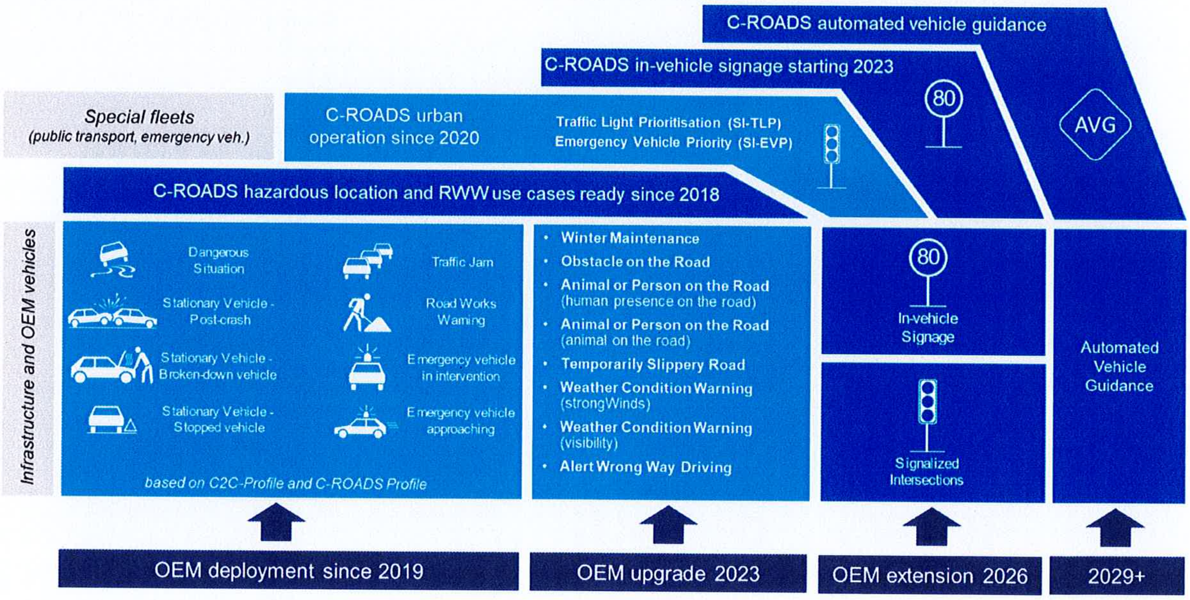

Figure 5.6. Overview of the development and integration of features into vehicle warning and automation systems by original equipment manufacturers (OEM), showing 'animal on road' warning being available in systems in 2023. Source: (Figure 1 in C-Roads 2024)

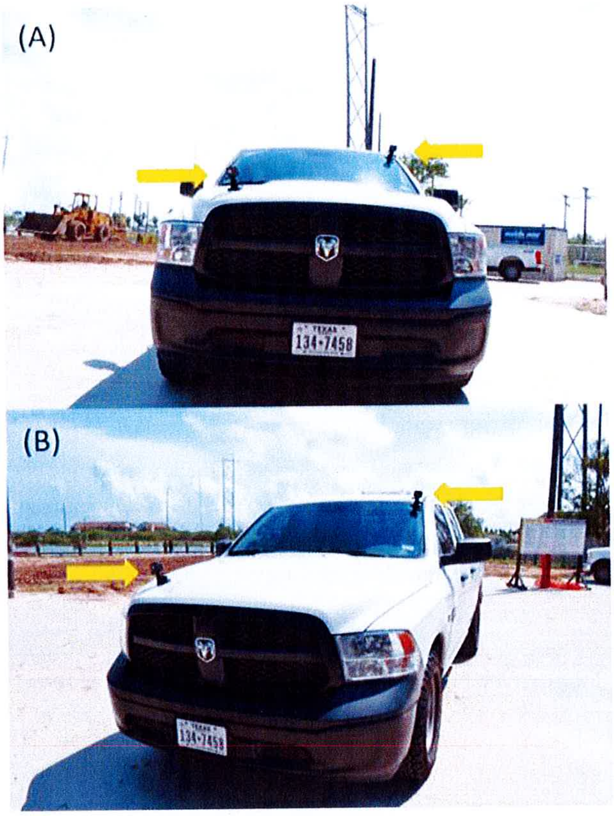

Figure 5.7. Vehicle-mounted camera-based animal detection systems designed for roadkill detection. Source: (Livingston 2019).

Figure 5.8. Examples of 'TurtleSAT' vehicle-mounted animal detection system imagery. *Source: Jim Steen, TfNSW*

In-vehicle detection based

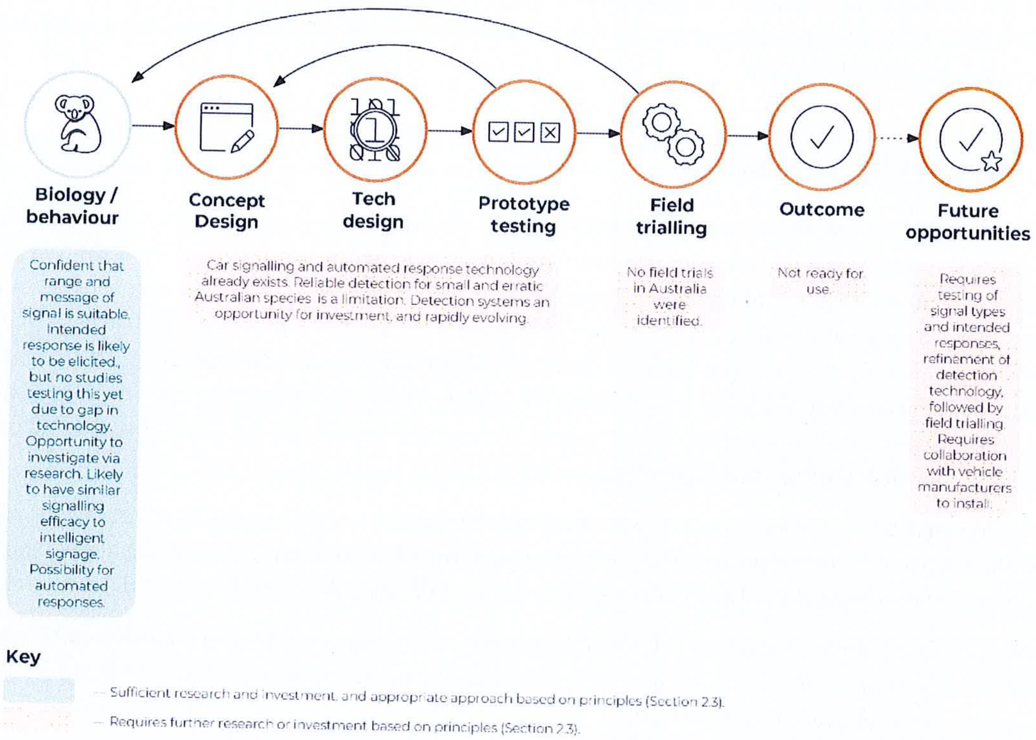

Figure 5.9 Qualitative assessment of in-vehicle signals with detection at reducing rates of WVC and identification of areas for further research and development.

6 Combined technology

The technological solutions described in Sections 3, 4, and 5 describe the typical components that make up many of the technological solutions that have been developed and trialled to reduce the rate and severity of WVC in Australia and globally. Importantly, many of these components can be combined and matched with other components or systems, producing new alternatives and systems.

6.1 At-grade crossings

At-grade crossings are WVC solutions that combine both physical and technological aspects, and there is potential to also include in-vehicle warnings. At-grade crossings are where wildlife are allowed or encouraged to cross the transport infrastructure in the absence of any wildlife crossing structure - i.e. they walk, hop, climb or fly over the road or railway. Intentional or managed at-grade crossings are where the fauna movement is aided with fencing, animal detection systems and/or intelligent or enhanced signage to increase the safety for wildlife and motorists (Huijser et al. 2015). Unmanaged or unintentional at-grade crossings are when animals enter the road or railway at any location in the absence of any controls (e.g. fencing) and motorists are typically not warned. This review assumes that at-grade crossings include some sort of animal detection and/or driver warning system.

At-grade crossings enable the movement of some species of wildlife but there remains a risk of collision with vehicles as fauna attempt to traverse the road or railway. There is also a risk of dehydration of species including turtles, amphibians and reptiles getting trapped between railway tracks (Kornilev et al. 2006, Budzik and Budzik 2014, Dorsey et al. 2015).

At-grade crossings for terrestrial animals are only feasible on roads and railways with low to moderate traffic speeds and low to moderate traffic volumes because wildlife need to cross the road between passing vehicles and vehicles are expected to slow down when fauna use the crossing.

A typical approach to facilitating safe at-grade crossings combines fencing, animal detection systems and signs. The fences funnel the fauna to a specific location where the at-grade crossing is encouraged or allowed, and vehicle operators are warned by enhanced signage, which is triggered by an animal detection system, that fauna are in close proximity and potentially about to cross the road or railway (Huijser et al. 2015). The at-grade crossing would ideally include mechanisms to stop animals moving along the road or railway away from the crossing location, such as electric mats or cattle grids (Section 4.1.1.3).

Managed or intentional at-grade crossings have been trialled and implemented in Utah USA and reduced ungulate-vehicle collisions by 37 – 42% (Lehnert and Bissonette 1997). A study of an at-grade crossing with fencing and animal-activated animal detection system with intelligent signage in Arizona USA (Figure 6.1) reduced elk-vehicle collisions by 97%, resulted in a 13% reduction in vehicle speeds and caused a 5.5-fold increase in motorist alertness when the signs were activated (Gagnon et al. 2019). Importantly, average speed reductions and braking response of motorists remained significantly higher over the nine-year period of the study when the signs were activated. A recent trial in Sweden (Bhardwaj et al. 2022) tested at an at-grade crossing with fencing and intelligent signage with thermal, radar, and infrared cameras to evaluate behaviour of deer and wild boar. During the one-year pilot study at a single site, three WVC occurred which was a 66% reduction in collisions after construction.

The effectiveness of at-grade crossings is influenced by the speed and volume of traffic, the behaviour of the target species (e.g. does it move quickly across the road or railway or linger in the danger zone), the effectiveness of the fencing at funnelling the target species to the crossing zone, the design and function of the animal detection system and signage, and whether it is safe for motorists to slow down at the location of the crossing.

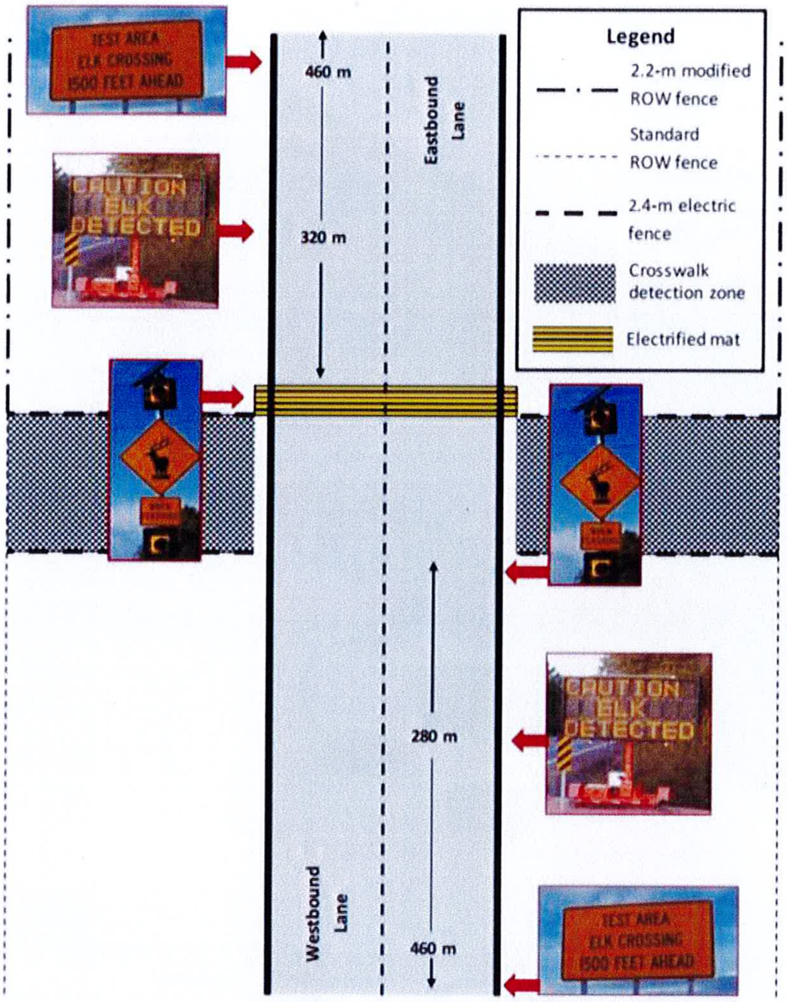

Figure 6.1. Layout of the at-grade crossing for elk on State Route 260, Arizona, USA, showing location of fencing, static signs and enhanced signs which functioned when elk were detected within the 'crosswalk detection zone'. Source: (Gagnon et al. 2019)

6.2 Combining animal detection systems, machine learning and intelligent signs

A recent trial in Queensland, funded by the NSW Department of Planning and Environment combined a CCTV camera with AI and machine learning to detect koalas, which then activated an intelligent sign to warn motorists of the presence of koalas (Zhou and Xing 2023). The prototype system (shown in Figure 6.2). was first tested within the Lone Pine Koala Sanctuary and subsequently tested on a road within the Nathan Campus of Griffith University. The researchers used various datasets to train the AI model to recognise koalas which improved reliability of the results over time.

The researchers concluded that the prototype had potential to mitigate WVC with koalas and other species of wildlife, as well as identifying ways to improve the system included power supply issues, improved koala recognition using other machine learning algorithms and the use of large image data sets to train the model.

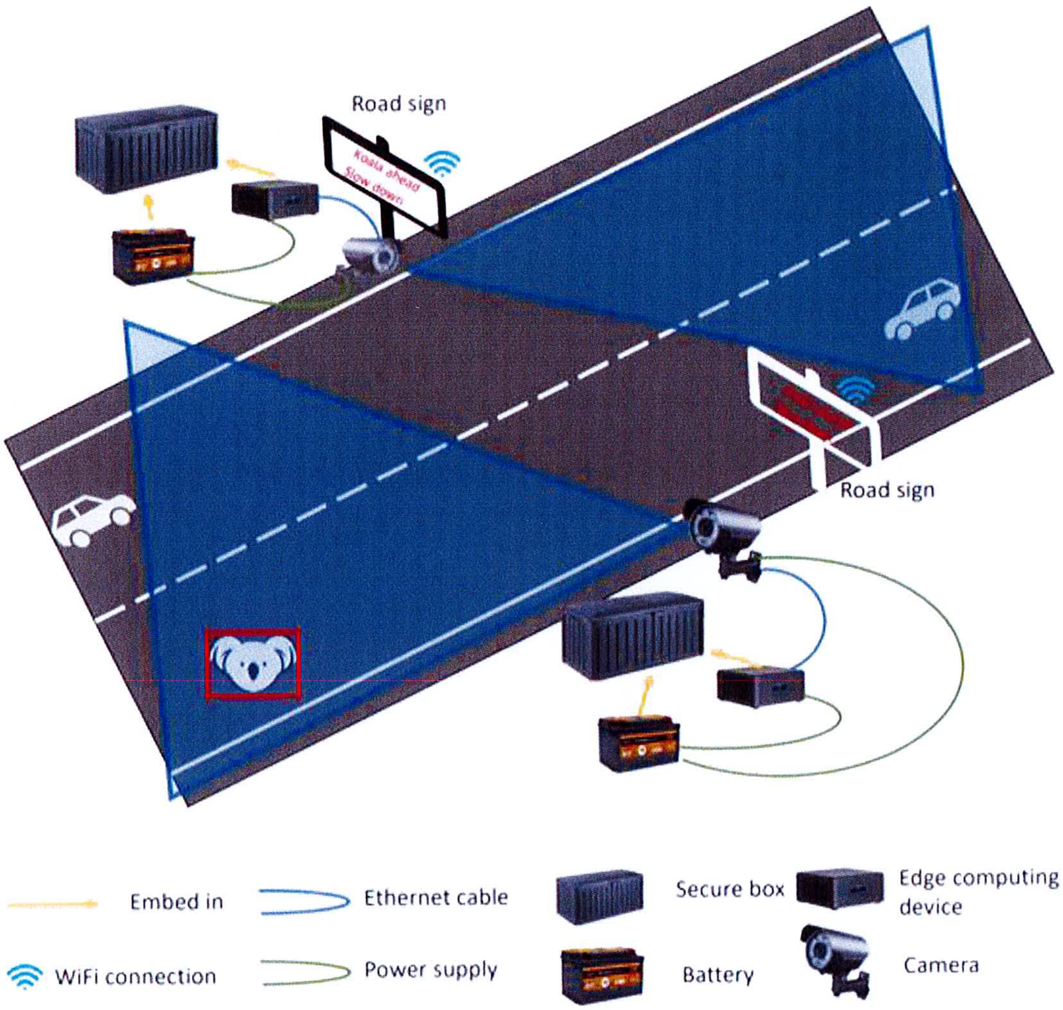

Figure 6.2. Conceptual design of intelligent signage prototype that processes real-time data from a CCTV camera about the presence of koalas and activates a warning sign. Source: (Zhou and Xing 2023).

6.3 Other combined systems

There are many potential combinations of components and systems that could conceivably be developed and tested to reduce the rate and severity of WVC. These combinations include:

— Combining at-grade crossings with in-car warnings, as well as the standard approach to include intelligent signs and in-car warnings advising motorists that they are nearing a high-risk area and pre-inform them of the appropriate action if a wildlife is detected.

— There is massive potential for connected vehicles to communicate with each other (vehicle to vehicle) and other infrastructure (vehicle to infrastructure) to both detect wildlife on the road as well as inform other vehicles and systems when they are responding to wildlife on the road or railway. For example, if a vehicle slows down in response to a warning from an intelligent sign or the in-car detection system has detected wildlife, other connected vehicles in the immediate area can also be warned and/or their automated response triggered (e.g. slowing down before reaching the incident zone). As shown in

- Vehicle-mounted animal detection systems can collect information about the presence of both living and dead wildlife on and adjacent to the road or railway, providing more accurate information about the distribution and abundance of wildlife, the location of actual WVC, and the identification of high-risk areas for WVC.
- Roads and railways are often constructed in close proximity to each other and within the same transport corridor. Detection systems on roads and railways could be integrated, as well as in-car and in-train warning and detection systems, and communicate with each other.

7 Synthesis and future direction

Physical solutions, such as fences and wildlife crossing structures, are currently the most effective technique to reducing and in some cases almost eliminating WVC for many species of wildlife. However, fencing can be prohibitively expensive to build and maintain, is difficult to install in some locations and is not effective for all species of wildlife.

Potential technological solutions to reduce the rate and severity of WVC are many, varied, at different stages of development and testing, and are often labelled as 'effective solutions' by developers and proponents. Unfortunately, the efficacy of many solutions, as revealed by rigorous testing, are often found to have limitations. In addition, many new technological solutions are still at early stages on the TRL scale (Figure 2.6) and have only been tested on a small number of species in limited settings and are yet to be widely deployed and tested.

Technological solutions are becoming increasingly complicated and can encompass one or more of the following elements:

- Systems that detect the presence of animals and/or vehicles.
- Systems that warn and aim to modify the response of vehicle operators
- Systems that warn and aim to modify the behaviour and/or responses of wildlife.
- Warning devices and detection systems can be mounted to vehicles and/or the side of roads and railways.
- Warning devices can include a range of visual, auditory or chemical signals.

There is great potential for technological solutions to reduce the rate and severity of WVC. Further development and testing of technological solutions is a high priority because the standard physical approaches (i.e. fences and wildlife crossing structures) are not feasible or able to be cost-effectively installed along all roads and railways. In addition, rates of WVC and the impacts of WVC on wildlife, people and vehicles is expected to increase with increased traffic volumes and the expanding transportation network. Finally, the timing for this development is opportune – the rapid growth and development of surveillance equipment and machine learning algorithms to process the vast quantities of data in real-time provides massive opportunities to effectively reduce the rate and severity of WVC.

TfNSW should collaborate widely with other transport agencies, AustRoads, ANET, industry and academic researchers in Australia and internationally to ensure the technology can be applied and implemented across jurisdictional boundaries.

This literature review and directions paper was prepared to inform and justify where TfNSW invests funding to mitigate WVC using technological solutions as part of a recent election commitment. The request for proposals for research and development trials of technological solutions should be issued to a wide group of potential providers, including academic researchers, industry groups, technology developers, and equipment and vehicle manufacturers.

It is critical to acknowledge that just as physical fences and wildlife crossing structures are not feasible or appropriate at every location, it is unlikely that technological solutions will be a panacea for all WVC problems. Research and development of the 'physical' solutions (e.g. fences, crossing structures) must continue and complement any future development of technological solutions. Importantly, trials of potential technological solutions must evaluate and acknowledge any limitations to ensure the proposed solutions are applied with full understanding of their effectiveness.

7.1 Effectiveness of different solutions

This literature review and consultation with experts at the symposium demonstrated that while a diversity of potential technological solutions have been developed and many are currently undergoing testing, none in their current form have consistently demonstrated significant reductions in the rate or severity of WVC in Australia or globally. The reasons for this are varied, including the use of inappropriate signals to warn wildlife and/or vehicle operators as well as the relative infancy of many technologies that are still being developed and applied to solving WVC.

The evidence to date indicates that the following technological solutions in their current form are not sufficiently effective to pursue further trials at this time:

- Reflectors – there is no evidence from Australia or internationally to indicate that reflectors mounted to posts on the verge or roads or railways to warn wildlife of approaching vehicles have any measurable effect on rates of WVC (Section 4.1.1.1).
- Standard signs to warn motorists of an elevated risk of WVC – at best achieve minor and temporary change in the driving behaviour of a small subset of drivers (Section 4.2.1.1). Wildlife warning signs are routinely ignored, especially when people do not observe or experience wildlife at or near the sign. Enhanced signs are slightly more effective than standard signs, provided they are specific to the problem at the location, are well-designed and are operational at specific high-risk times of the day or year (Section 4.2.1.2).
- Virtual fencing, in its current state, is not recommended for in-situ trialling on roads or railways in NSW or Australia (Section 5.2.1.1). Wayside deterrents have limited effect because the effectiveness of the specific auditory and visual stimuli at alerting different species is unknown, the ability of target species to hear the stimuli above traffic noise and other disturbance is also unknown, and the ability of the system to trigger the appropriate response of target species is unknown. Further development and testing of biologically relevant stimuli is recommended as a next step.
- Currently available whistles and other auditory deterrents attached to the front of vehicles (Section 4.1.2) appears to have little effect on rates of WVC for similar reasons to virtual fences (see preceding point).
- Traffic calming can be effective at reducing traffic volume and/or traffic speed on low-volume and low-speed roads which reduces rates and severity of WVC – but is not appropriate on high-speed and/or high-volume roads (Section 3.2.1).

7.2 Directions for research and development

Technology is developing rapidly and many technical and computing aspects that limit the effectiveness of current prototypes or systems will become less constraining in the not-too-distant future. The highest priority actions and directions for research and development should focus on technologies and components that can be incorporated into a suite of combined systems and solutions (Section 6).

Future testing and trials should be undertaken using scientifically robust approaches that are conducted throughout product development (i.e. at concept, lab-testing and in-situ stages outlined in Figure 2.7) to maximise the likelihood that effective solutions can be created.

The following over-arching recommendations and conclusions apply:

- Collaboration with other transport agencies, AustRoads and relevant industry groups to fund, support and implement research and development of technological solutions that can be applied and implemented across jurisdictional boundaries is a high priority.
- Despite the recent acceleration in technological development and sophistication, fully effective solutions for all species, contexts and situations are unlikely to be developed soon. However, there will be many aspects and components that are tested and found to be effective, and these advancements should be identified and further developed to advance this field of WVC mitigation. Ongoing funding and support are required to develop research and development pipelines and test efficacy in a systematic, co-ordinated and scientifically robust way over at least the next ten years.
- Set up an industry taskforce / development group including ANET, Austroads, car manufactures and their component suppliers, industry, and academic researchers to progress the development of different technologies with co-sponsored research bids, proposals and projects.
- Send the call for research, development and testing to university researchers, industry technology and data specialists and developers to collaborate and develop technological solutions to WVC.

Fourteen specific recommendations have arisen out of this review and synthesis, with the first four focusing on overarching supporting frameworks or understandings that apply regardless of which technological solution is implemented, Recommendations 5 – 7 focus on developing effective animal detection systems, Recommendations 8 and 9 focus on how the information from detection systems can be applied, Recommendations 10 and 11 focus on animal deterrent systems and Recommendations 12 to 14 are stand-alone considerations.

1. **Ensure signalling theory underpins research and development of all technological solutions:** Signalling theory is critical to ensuring the most appropriate signals are being propagated, that the intended target can detect the signal with sufficient time to respond and that the response is appropriate and consistent over time. Signalling theory must be integrated with the technological considerations to ensure that the solution is both ecologically sensible and technologically reliable.
2. **Adopt the Technology Readiness Level scale and the Evaluation Framework** (Figure 2.7) **to develop and evaluate system effectiveness:** The TRL scale (Figure 2.6, Table 2.1) provides a globally-recognised framework to evaluate the maturity of technological solutions to WVC and the Evaluation Framework used in this review (Figure 2.7) provides a practical approach to guide the development and evaluation of technological solutions. Both frameworks should be used by developers and transport agencies to guide the development, funding, testing and certification of potential solutions.
3. **Establish a national roadkill reporting platform:** Many physical (e.g. fences and crossing structures) and technological solutions (e.g. vehicle-operator warning systems), require reliable data on WVC hotspots to function efficiently. TfNSW, in collaboration with other transport agencies across Australia, should prioritise the establishment of a roadkill (which includes wildlife killed on railways) reporting application and data storage facility, with ability for data to be input by various sources, including wildlife carers, researchers conducting targeted surveys, roadkill carcass collection teams, incidental observations from community members, etc. The system must include appropriate quality control mechanisms, and should apply across state boundaries and transportation types, as in-vehicle systems must function across Australia.
4. **Implement targeted and general driver education and awareness programs to maximise the success of technological solutions that rely on an appropriate response from vehicle operators:** Vehicle operators must understand the system being applied (e.g. at-grade crossing, a general warning of an increased risk of collision in a broad area or is it a warning of an impending WVC) and be guided to respond in the appropriate way (e.g. increase vigilance, slow down a little, slow down significantly, etc). Relevant, timely and effective education is essential to ensure motorists respond appropriately to different signals without increasing the risk of adverse outcomes, such as vehicle-vehicle collisions or dangerous driving. Teaching motorists about WVC and how to respond in the absence of any technological solution would also be of great benefit.
5. **Develop animal detection systems for Australian wildlife:** Most animal detection systems are focussed on large-bodied animals, such as elephants, deer, bears and wild boar, because they are easier to detect and identify and cause the greatest damage to vehicles and occupants. Research and development for small species, and macropods that hop and move unpredictably is urgently required to apply these technologies in Australia. This would focus on the systems to detect wildlife as well as the AI and machine learning algorithms required to identify species and reduce false positives.
6. **Investigate and develop the use of existing infrastructure to detect animals:** Many local councils and transport agencies have CCTV and other surveillance cameras to monitor road networks and other facilities and this equipment may be able to detect wildlife at relatively low cost. This information could then be used to activate relevant warning systems.
7. **Use in-vehicle animal detection systems to detect living and/or roadkill animals and build accurate and real-time maps of WVC hotspots or high-risk areas:** Systems are currently being developed and used to identify turtles on the road (1 Million Turtles) and assess pavement condition for road maintenance (Austroads 2022) to create static maps. These systems should be further developed to provide real-time updates from detection systems in connected vehicles.

8. **Use animal detection systems to intelligent wayside signage and/or in-vehicle warning systems:** Animal detection systems mounted to vehicles and/or installed on the side of roads and railways can provide real-time warnings of potential WVC to intelligent signs and/or in-vehicle warning systems. Real-time warnings will improve the reliability and meaningfulness of the signal and enhance compliance.
9. **Develop in-car or app-based warning systems to warn vehicle operators when they enter a high-risk WVC area at a high-risk time:** The in-car system is based on spatially explicit WVC data and/or habitat suitability modelling which can be updated as new WVC data is obtained. A mobile-phone app-based system could be developed and deployed relatively quickly, providing immediate benefit to vehicle operators, especially those in older cars that lack sophisticated satellite navigation systems.
10. **Support research on the effectiveness of biologically relevant animal deterrents:** The identification and testing of species-specific stimuli that warn different target species of approaching vehicles will enhance the effectiveness of wayside- and vehicle-mounted animal deterrents. These stimuli will vary by species and testing should consider biological and ecological relevance, and be focused on minimising the likelihood of habituation.
11. **Undertake research on the effectiveness of wayside- and vehicle-mounted deterrents on trains:** Collaborate with state and national train operators (e.g. Australian Rail Track Corporation) to test relevant signals (identified in Recommendation 10) specifically on railways, as these systems are likely more effective in the long-term on railways that roads due to fewer vehicle movements which reduce the likelihood of habituation. These should include animal detection systems and/or be targeted to WVC hotspot areas.
12. **Consider animal-borne tags which activate intelligent signs or in-car warnings in specific situations and locations:** This approach might be suitable for a high-profile species where the WVC hotspot is constrained to a specific area. This system should complement in-car detection and vehicle operator systems.
13. **Electric mats should be developed and trialled for future use:** Electric mats have potential to enhance the effectiveness of fencing where gaps due to fence ends and access roads are unable to be avoided. Trials should focus on developing solutions for a range of Australian wildlife, including macropods who can jump over such mats.
14. **Undertake controlled trials of increased illumination (e.g. light-coloured pavement, overhead lighting) to increase detectability of wildlife and modify driver response:** There are increasing calls from the community to install overhead lighting or use light-coloured pavements to reduce rates of WVC by increasing the detectability of wildlife and subsequently modifying driver behaviour. Scientifically robust trials in controlled environments that measure detectability of wildlife in response to relevant variables, such as the size, colour, shape and movement of wildlife, vehicle speed, time of day, headlight brightness, weather conditions, and moon phase, etc., are required. If these pilot studies indicate a potentially positive response, move to well-designed on-road trials (see Section 7.3) and measure actual driver responses and rates of WVC.

7.3 Guidance for conducting research, development and field trials

All future research and development and field trials must be undertaken to the highest possible scientific and experimental standards and protocols to maximise the quality of the data that can be collected and the strength of the inference that can be made.

The following topics/issues should be considered:

— Research and development trials should measure parameters relevant to the specific stage of development of the solution in the Technology Readiness Level. For example, early-stage trials are likely to measure animal responses to stimuli or distances over which animal detection systems function, with field trials on live roads or railways focussing on measuring relevant parameters such as driver responses, animal responses, and ultimately, rates of WVC and the severity of those collisions.

- Trials must measure the degree of effectiveness of a component or potential solution to enable a comprehensive comparison of the costs and benefits of multiple options to reduce rates of WVC. For example, transport planners may weigh up the per km cost to install and maintain a fence with a (say) 85% effectiveness vs the cost and effectiveness of a suite of potential technological solutions.
- Trials conducted at each stage in the development of a potential solution must be scientifically robust and have the strongest possible experimental study design. This typically includes measuring rates of WVC (or other relevant parameters, such as vigilance or flight of animals exposed to a stimulus, response of vehicle operators) before and after the intervention at multiple control and treatment sites. Blind trials could also be considered – where the person collecting the data does not know if the technology is operational or not – to minimise unintentional bias.
- Trials should calculate the statistical power of the study required to detect a significant effect, if one exists. Trials with a low effect size, or a variable response, will require more sampling effort to detect a significant effect than a large or consistent response. For example – it is easier to measure the effectiveness of a physical fence that eliminates WVC at a hotspot compared to an animal deterrent system that reduces the rate of WVC by 10%. Ecological statisticians should be consulted to advise on the design of studies, with a focus on the minimum number of replicates and/or the duration of the study required to draw the strongest possible inference.
- Trials should aim to test the effectiveness of the technological solution for a range of species of wildlife under different road/railway, vehicle and environmental conditions. For example – how well does the solution work under different traffic speeds or traffic volumes, road widths, adjacent habitats, topography, land-use, etc. Trials will likely need to be staged to comprehensively address these various considerations.
- Research and development of technological solutions and supporting systems should take into consideration future environmental conditions, including climate changes and the distribution and abundance of non-native large-bodied mammals in Australia (e.g. deer, wild horses, wild pigs, etc). Fortunately, much of the research and trials in North America and Europe are focussed on these species and these may be applicable to the Australian situation.
- Each technological system and ideally the components in each system must demonstrate reliability and have verifiable results for each of the TRL stages. In other words – don't run a fully-blown field trial of a 'final' technological solution without first demonstrating success at each of the preceding intermediate stages.
- Trials should also consider and test for habituation of wildlife and people to signals – long term success is critical.
- The actual effectiveness of the signal at reaching the receiver must be tested and measured, both initially (i.e. during concept stages and at the start of trials) but also during the trial, to ensure the product is technically working as it should. For example, an acoustic stimulus may not travel as far as claimed by manufacturers or it might be outside the hearing range of the target species. Importantly, if the technology fails during a trial, it must be quickly identified and rectified to ensure the results are valid.
- Trials must collect quantified and reliable data and avoid relying on anecdotal data to demonstrate success. Trials must include actual counts of relevant parameters (e.g. animal behaviour, vehicle-operator responses, roadkill), be targeted to specific areas, with a consistent survey effort throughout the trial and be consistently conducted in identical ways before, during and after the trial. New approaches and methods to data collection should be considered (e.g. vehicle-mounted detection systems) to record WVC.
- The evaluation framework used to evaluate the effectiveness of different solutions can also be used by technical solution developers to guide and inform the development process.

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