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Manual

Fauna Sensitive Transport Infrastructure Delivery
Chapter 6: Mitigation

June 2024

Queensland Government

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Note:

The dimensions and recommendations for mitigation measures described in this Chapter have been developed from similar guidance prepared for:

- the Australian Rail Track Corporation (ARTC) for the Inland Rail Project.
- Major Road Projects Victoria (MRPV).
- Transport for New South Wales (TfNSW).

Where necessary, the guidance and recommendations have been adapted for use and conditions in Queensland.

This approach, conducted with the support of MRPV, ARTC, and TfNSW, ensures similar best-practice can be adopted and consistently applied along the east coast of Australia.

Key Points

- Mitigation measures are implemented on transport infrastructure projects to address fauna impacts that are unable to be avoided or minimised. Mitigation measures can reduce the scale, intensity or duration of impacts from a project and if successful, can remove the need for offsets if any residual impacts are not significant.
- Mitigation measures can be structural or non-structural, and include:
  - Wildlife crossing structures to reduce the barrier effect of the transport infrastructure and facilitate fauna movement.
  - Fencing or other techniques to reduce the rate of Wildlife Vehicle Collision (WVC), fauna injury, and mortality, and to improve human safety.
  - Habitat enhancement along transport infrastructure and at crossing structures to enhance use or support population recovery (e.g. strategic revegetation, replacement hollows, artificial shelters).
  - Management of vegetation and other habitat features along roadsides and railways to reduce the attraction of such areas to fauna and improve motorist and fauna visibility.
  - Features and designs of transport verges and crossing structures to reduce the severity of noise and light impacts.
- Different types of mitigation measures offer different functions for different species. Details are provided on how to deliver each mitigation measure effectively, as well as:
  - The aims and objectives of each mitigation option.
  - Where to install them.
  - How many to install.
  - Design details.
- Some mitigation measures, such as signage and acoustic deterrents, have limited or uncertain effectiveness and require more development and testing to quantify their degree of efficacy.

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1 Introduction

1.1 Objectives of mitigation

Mitigation measures are implemented after all opportunities to avoid and minimise (Chapter 5) have been identified and implemented where feasible.

There are two broad objectives of mitigation:

1. Reduce impacts to fauna, such as barrier effects, mortality from WVC, fauna disturbance from traffic noise and Artificial Light At Night (ALAN), environmental pollution, weed invasion, etc.
2. Improve motorist safety and reduce vehicle damage (e.g. truck, car, rollingstock) by reducing the rate and severity of WVC and near-misses.

1.2 Types of mitigation

There are three broad categories of mitigation:

1. Wildlife crossing structures and other design features (e.g. canopy connectivity) to enhance ecological connectivity and fauna movement across transport infrastructure (Sections 2 to 12).
2. Fencing and other methods (e.g. traffic management, vegetation management, fauna management) to reduce rates of WVC while simultaneously improving human safety and reducing damage (e.g. to train locomotives) (Section 13 to 15).
3. Biodiversity enhancements and infrastructure designs to reduce the severity of the REZ and improve habitat quality along or around roads and railways. (Sections 16 to 19).

It is critical that the mitigation measures implemented are effective at addressing the specific impact and Chapter 6 discusses the process to develop an optimal suite of solutions. For example, wildlife crossing structures primarily address the barrier effect of roads and railways and should be implemented when trying to maintain ecological connectivity. Fauna exclusion fencing is the primary approach to reduce rates of WVC, and they also improve rates of use of crossing structures by funnelling fauna to them. Plantings, noise walls, and landscaping can reduce the severity of noise, light, and chemical pollution to varying degrees.

Mitigation measures are usually installed as an integrated suite that addresses multiple impacts. For example, wildlife crossing structures are almost always installed with fauna fencing to funnel wildlife to the crossing structure and reduce WVC. Habitat enhancements, mitigation measures for noise and light, and escape mechanisms on fences are also often installed on most projects, along with crossing structures and fencing. Mitigation measures can also be partnered with targeted community education campaigns.

2 Improving ecological connectivity

The primary approach to improving fauna movement across transport infrastructure is with wildlife crossing structures that allow for the safe passage of fauna above or below the road or railway[1]. Crossing structures are usually implemented in conjunction with other measures such as fencing (Section 13) and the enhancement and/or management of habitat (Section 16). The primary aim of crossing structures is to maintain connectivity, and the primary aim of fencing at crossing structures is to direct fauna to crossing structures and prevent WVC.

There are numerous types of crossing structures, and they are commonly grouped into two categories (Table 2(a)):

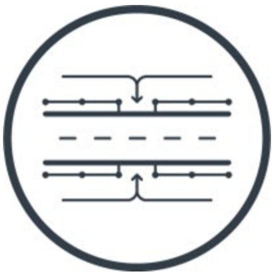
- Underpass: A structure or design that allows fauna to pass beneath the road or railway and includes bridges and culverts.
- Overpass: A structure or design that allows fauna to pass above or over the top of the road or non-electrified or viaduct railway and includes vegetated land bridges, cut and cover tunnels, canopy bridges, and glider poles.

Other strategies (e.g. traffic calming, reduced vehicle speeds, vegetation management, and at-grade crossings) improve the chances of fauna successfully crossing the road or railway 'at-grade' by reducing the risk of WVC. Unlike crossing structures, they do not eliminate the risk of WVC, and are thus only implemented in very specific situations.

Table 2 – Main types of wildlife crossing structures

CATEGORY	CROSSING TYPE	PICTURE
Underpasses	Bridge underpass (Section 3)	
	Culvert (Section 4)	

[1] (Smith et al. 2015)

CATEGORY	CROSSING TYPE	PICTURE
	Fishway (Section 5)	
Overpasses	Vegetated land bridge (Section 6)	
	Rope-ladder canopy bridge (Section 7) (can also be under bridges – Section 8)	
	Glider poles (Section 9) (can also be under bridges – Section 10)	
	Canopy connectivity (Section 11)	
Other strategies	At-grade crossing (Section 12)	

2.1 *Summary of crossing structure types by species*

Different species of fauna have different habitat preferences (e.g. dense forest, open grassland, waterways, etc.), movement modes (e.g. flying, hopping, crawling, etc.) and movement capabilities (e.g. fast or slow moving, avoid open areas, etc.). Therefore, different types and designs of crossing structures are required to maintain connectivity across transport infrastructure projects for different fauna species.

Table 2.1 provides a quick summary of the types of crossing structures suitable for different species of fauna. This summary Table also identifies which crossing structures or design features have the potential to work but require further research and testing to confirm adequacy before widespread implementation.

Table 2.1 – Overview of typical suitability of different types of mitigation measures for species groups in Queensland

Chapter	Species group	Bridge underpass	Culvert	Vegetated Land bridge	Canopy bridge	Glider poles	Canopy connectivity	At-grade crossing	Fencing	Escape Mechanism	Enhanced signage, animal detection systems
	Section	3	4	6	7 8	9 10	11	12	13	15	19.7 19.8
9	Birds: flying	P	-	O	-	-	P	P	-	-	-
9	Birds: non-flying	O	P	O	-	-	-	-	P	P	?
10	Flying-foxes	P	-	O	-	-	P	P	-	-	-
11	Microbats	P	P	O	-	-	P	P	-	-	-
12	Macropods	O	O	O	-	-	-	-	O	P	?
13	Koalas	O	O	O	-	-	-	-	O	?	?
14	Possums	O	P	O	O	-	P	-	P	?	-
14	Gliders	P	-	O	O	O	O	P	-	?	-
15	Small mammals	O	P	O	P	-	-	-	O		-
16	Semi-aquatic mammals	O	O	?	-	-	-	-	?	-	-
17	Reptiles	O	O	O	?	-	?	-	O	?	-
18	Amphibians	O	O	P	?	-	?	-	O	-	-
19	Fish	O	P	-	-	-	-	-	-	-	-
20	Invertebrates	O	P	O	?	-	?	P	-	?	-
21	Dingoes	O	O	O	-	-	-	P	O	?	?

Notes:

O = Optimal solution.

P = Possibly suitable solution which applies when different species within the group have very different requirements.

? = unknown, more research needed.

- = unsuitable solution.

The following is additional information to consider when using Table 2.1:

- Refer to relevant species profile and solution specification tables for detailed information to inform design.
- Fencing and crossing structures should always be installed together to mitigate WVC and restore connectivity.
- Unsuitable techniques for all species are not given in table e.g. odour and chemical repellents (Section 19.1) and standard signs (Section 19.7) are not shown.
- Acoustic and visual deterrents (Section 19.2) (e.g. virtual fencing) require more research before their effectiveness is known and are not shown in Table 2.1.

Biodiversity enhancement (Section 16), replacement hollows (Section 17), and timber re-use (Section 18) can be used for most fauna groups and are not shown in Table 2.1.

2.2 Multi-use wildlife crossing structures

Multi-use wildlife crossing structures are underpasses and overpasses that facilitate the movement of fauna as well as additional uses, such as drainage or the movement of people, livestock, or farm machinery. The degree of 'multi-use' can range from intentional simultaneous use (i.e. both functions given equal priority in the design) to incidental use by fauna (i.e. primary aim is something other than the movement of fauna).

Multi-use crossing structures can be a cost-effective approach to achieving fauna connectivity, however such structures must be carefully planned and designed to ensure that fauna movement is not compromised[2]. It is not acceptable to label a drainage culvert a multi-use culvert without including specific design features to facilitate the movement of fauna.

The effectiveness of multi-use crossing structures for fauna and other uses depends upon the frequency and timing of use by both groups as well as the extent to which both uses can be physically or temporally separated[3]. For example, a wildlife crossing structure with a shared use path in a residential area is unlikely to function effectively for fauna because people are likely to use it throughout much of the day, including at dawn and dusk. In contrast, an underpass on a rarely used walking trail in a remote areas may perform satisfactorily for fauna. Similarly, a box culvert used occasionally by livestock may function satisfactorily for some fauna.

The design of multi-use crossing structures should be based on the requirements for the multiple uses, with a focus on maximising the benefits for the target species of fauna, rather than the other use(s). Details for multi-use bridge underpasses, culverts, and land-bridges are given in Sections 3, 4, and 6.

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[2] (van der Grift et al. 2011)
[3] (Van der Grift and van der Ree 2015)

2.3 A note on crossing structure dimensions

The dimensions of underpasses and overpasses provided in this manual represent the recommended sizes based on evidence, best knowledge to date and understanding of the use of the different structures by target fauna that are derived from monitoring programs across eastern Australia. These recommendations are based on rates of use by a majority of animals, most of the time, and excludes sporadic instances of low numbers of animal using suboptimal structures such as an animal using a very small structure on one occasion. It is important to note that in most cases, a slightly smaller crossing structure compared to those given in this manual is unlikely to result in a 'failed' structure – it typically results in lower rates of use. Therefore, in situations where an optimally sized structure is unable to be installed due to project constraints, it may be compensated for by installing more slightly smaller crossing structures over a larger area.

The dimensions of a crossing structure selected for a project are also influenced by a range of other considerations, such as the topography (slope, and the height of any fill or depth of cuts), the cut and fill balance on a project, and the proximity of the adjacent vegetation and the amount of clearing required for construction of the crossing structure, etc.

The following guiding principles should be used when selecting the size of a structure:

- Use the dimensions provided in this manual wherever possible.
- All crossing structures should be as short as possible.
- The height and width of underpasses, and width of vegetated land bridges, should be as large as possible.
- The longer the crossing structure, the larger the cross-section should be.
- The target species must be able to physically fit in the structure while moving.
- Larger structures provide more opportunity for inclusion of fauna furniture and habitat creation than smaller structures.
- Smaller crossing structures may be suitable in some circumstances, especially for retrofits (i.e. adapting an existing drainage structure and making it suitable for fauna).
- Any deviations from the recommended sizes must be strongly justified and should be considered a 'trial' and be accompanied by a monitoring and evaluation program. It is important these trials are scientifically robust in order to quantify any reductions in effectiveness or rate of use and results shared to reliably inform future projects.
- Species experts and suitably qualified transport ecologists should be consulted when proposing crossing structures with alternative dimensions to those identified in this manual.

3 Bridge underpass

Bridge underpasses enable the movement of wildlife under the road or railway and range in length from single-span bridges to multi-span bridges and viaducts. Bridge underpasses range in height from at least 1 metre above the ground to up to 10 or 20 metres at viaducts which cross steep valleys. Most bridge underpasses are typically 3–5 metres above the ground. Underpasses are often used where the transport infrastructure crosses waterways, deep valleys, or areas prone to flooding. Pedestrian or cycle ways (shared user paths) are often constructed as underpasses.

Bridges and viaducts are generally the most effective type of underpass for fauna[4] because they are larger and more open than culverts and are therefore used at higher rates by a greater diversity of species than smaller underpasses. Larger-bodied species of fauna and species that avoid enclosed spaces also appear to prefer bridge and viaduct underpasses over smaller underpasses, such as culverts. Bridge underpasses may also have a natural substrate which can support more shrubs, logs and other habitat features than culverts, also encouraging use by fauna. In addition, bridge designs can be modified in the following ways to accommodate movement of fauna:

- Increasing span length to increase openness and provide space above water levels for dry passage.
- Raising bridge height to increase openness and provide headroom for taller species (however rail bridge heights may not be easily modified due to associated rail geometry).
- Separating the bridge into multiple carriageways to facilitate growth of vegetation under and between the bridge structures.

Bridges disrupt the flow, velocity, and structure of waterways significantly less than culverts. The Queensland Department of Agriculture and Fisheries (DAF) have specified that new bridges without structures in the waterway channel, as well as potentially multi-span bridge, do not constitute waterway barrier works[5] because the waterway is relatively untouched. Importantly, bridge underpasses are typically open and are therefore less of a behavioural and physical barrier to the movement of fish and other aquatic species in the waterways [6].

Wherever possible, bridge underpasses should be used rather than culverts where fauna movement is a high priority.

Table 3(a) – Design considerations for bridge underpasses

ASPECT	DESIGN CONSIDERATIONS
Target species	• Proven for aquatic species (fish, macroinvertebrates) and semi-aquatic species (platypus, turtles, amphibians). • Proven for a wide range of terrestrial fauna (macropods, koala, small terrestrial mammals, reptiles). • If large enough (tall and/or wide) and with appropriate design features or furniture, target species can include arboreal species (with glider poles or canopy bridges)[7], birds including Cassowary[8] and microbats[9].

[4] (Bhardwaj et al. 2017, Denneboom et al. 2021, Jensen et al. 2023)
[5] (DAF 2019)
[6] (Austroads, 2018)
[7] (van der Ree unpub. data)
[8] (Goosem et al. 2011, Department of Transport and Main Roads 2020)
[9] (Bhardwaj et al. 2017)

<table>
<tr><th>ASPECT</th><th>DESIGN CONSIDERATIONS</th></tr>
<tr><td>Design, dimensions and construction materials</td><td>
For all drainage structures, investigate feasibility of replacing culverts with bridges.
The section of the bridge spanning the waterway should not have any in-stream support structures.
If in-stream support structures are required (e.g. piles), these should be located outside of the low flow channel. This ensures suitable depth of water during base flow periods and prevents obstruction of the low flow channel.
Ensure both terrestrial and aquatic fauna are accommodated with a drainage and aquatic fauna zone and a terrestrial fauna zone.
Bridge abutments should be placed outside the waterway channel and ideally above the high bank and set back to create a terrestrial fauna zone (Figure 3(a)).
Preferred terrestrial fauna zone requirements:

Dedicated to terrestrial fauna movement, and does not include space required for pedestrian paths, vehicle access roads, rip-rap / erosion control, etc.
On both banks of the waterway and as flat as possible, whilst also maintaining a profile as close as possible to banks upstream and downstream of the bridge. On steep banks, the wildlife zone can be narrower than specified.
Set outside of the high bank to remain dry year-round except during flood events.
As wide as possible. Optimal width depends on target species (Table 3(b)). For early planning purposes when target species may not be known, use a minimum width of 2 metres.
As tall as possible. Optimal clearance depends on target species (Table 3(b)). For early planning purposes for terrestrial species use a minimum height of 2.4 metres. For arboreal species, minimum height is 5–6 metres.
The minimum height and width requirements for bridge underpasses is provided in Table 3(b).

Maximise natural light levels in the underpass by keeping the bridge as narrow and high as possible. Minimum natural light levels are dependent on the requirements of the target species and expert advice should be sought.
Consider separating carriageways on low bridges by at least 5 metres to allow light and water to reach the ground and support growth of natural vegetation. Install fauna fencing between the two carriageways to prevent fauna from accessing the road or railway via the central median strip. Ensure any rain or flood water that enters via the median can drain away. Carriageways do not need to be separated on tall viaducts.
</td></tr>
<tr><td>Inundation and dry passage</td><td>If it is not possible to include a terrestrial fauna zone, consider alternative dry passage options such as a ledge or shelf installed on or immediately adjacent to bridge abutments. The shelf must connect to terrestrial habitat at both ends and be made from non-biodegradable material (e.g. concrete, rock) or timber.

Minimum 500 millimetres wide, ideally 1 metre wide subject to hydrological constraints. Minimum 600 millimetres clearance from the underside of the bridge for smaller fauna (e.g. koala, echidna) and 2 metres clearance for large fauna (e.g. kangaroo).
Shelf or ledge height to be as close to the natural ground level as possible while achieving dry passage most of the time (set above the 1:10 year flood level if practicable).
</td></tr>
</table>

ASPECT	DESIGN CONSIDERATIONS
Landscape position and fencing.	• General siting guidelines for bridges that cross a waterway: – Avoid crossing waterways near sharp bends, sections of unstable bank or naturally strong “riffle” systems. These areas act as natural important bank stabilisers and often provide essential habitat pools. Any alteration of these systems may impact habitat, change bank stability, and initiate riparian erosion. – Avoid works that change the frequency and spacing of existing natural habitat pools and riffle systems. • Avoid, or where possible, re-design or remove potential barriers that may limit fauna access to the bridge underpass, such as adjacent fences, roads, or railways. • Install fencing to funnel the target species to the bridge wherever there is a risk that the target species may access the road or railway. The length of fencing is site- and species-dependent, refer to Section 13 for guidance. • Fauna fencing may not be required if the bridge underpass is much easier for fauna to use than attempting to cross the road or railway at grade and the adjacent sections of road or railway are on steep or tall abutments or there are design features that prevent fauna from access the road or railway. • Fencing needs to tie into the bridge structure to prevent fauna squeezing past (Figure 3(a)). • Fencing must consider the risk of flood and being damaged during floods and/or debris becoming lodged in the fencing and obstructing the flow of water.
Landscaping and vegetation	• Where possible the waterway should be kept as natural as possible. • Any channel Section that has been diverted, reprofiled, and/or created must be rebuilt to be as natural as possible allowing for natural features such as vegetation, rocks, and leafy woody debris to be present. • Banks upstream and downstream that are disturbed as part of the works should be reprofiled to be consistent with existing conditions and banks must be revegetated with locally appropriate riparian vegetation. If existing banks are highly disturbed, then reprofile and revegetate to improve conditions. • Vegetation should be planted at the entrance of bridge underpasses to encourage fauna to use the structure (Section 16.2) • Allow vegetation and habitat suitable for the target species to grow under the bridge as much as possible, maximising protection and shelter needs for target species. Consider different habitat zones under bridge to ensure habitat for species with different requirements. • If erosion or scour control is necessary: – Minimise scour protection in the terrestrial fauna movement zone as this inhibits movement of terrestrial fauna and can create traps and barriers for movement for fish and other aquatic species during low flow periods. If scour protection is required, use concrete or small rocks instead. – Small piles of large rocks (e.g. >30 cm diameter) are generally beneficial for amphibians as they provide inter-rock shelter spaces. – Ensure there is a clear passage end-to-end, with no pools or puddles that can entrap fish. – Where very large rocks (>30 cm diameter) are required, they should be embedded into the channel bed to prevent water pooling beneath and trapping fish and to secure them during floods.

ASPECT	DESIGN CONSIDERATIONS
Furniture and enhancements to encourage use and reduce the risk of predation	• Instream woody habitat provides habitat and facilitates use of the crossing structure for aquatic species and should be considered where it can be installed without damaging bridge infrastructure. Furniture and enhancements for terrestrial habitat: • Fauna furniture can be installed at the entrance and along the length of the structure depending on the target species. Fauna furniture should be a combination of artificial shelters and natural features that suit the target species (e.g. logs, rocks, wood piles) to provide shelter from predators and improve habitat suitability. Furniture can be installed on the ground, attached to walls, or built into the structure itself (e.g. bat roosts built into the bridge deck or beams). • Use a combination of wooden and non-biodegradable artificial shelters, in accordance with Section 16.7. If future access under the bridge is likely to be restricted, with limited ability to replace or maintain fauna furniture, use only non-biodegradable furniture. • With sufficient clearance, bridge underpasses can include additional structures to provide alternative pathways and allow fauna to avoid predators: – Bridges with clearance >~6 m can include canopy bridges (Section 8) and glider poles (Section 10). – Elevated horizontal logs for arboreal mammals or log rails – refer to Section 16.8. – Refuge poles with resting platforms to provide koalas refuge from predators—see Section 16.8. – Horizontal logs for small mammals (Section 16.8). – If a bridge underpass is for arboreal mammals, retain trees as close to the bridge as possible, and ideally retain a strip of lopped trees underneath. If trees can't be retained, undertake strategic revegetation and/or re-install pruned trunks or standard poles as glider poles or for canopy bridges. Furniture and enhancements for aquatic habitat: • Bridge underpasses would ideally leave the waterway untouched. If beneficial, aquatic habitat can be enhanced through the installation of root balls, long underwater non-kinetic embankment replacement (LUNKER) pipes, and other aquatic enhancements (Section 5).
Lighting	• Where possible, avoid artificial lighting within bridge underpasses or within 100 metres of bridge underpass entrances. • Where lighting is required to meet safety standards (Section 19.5).
Maintenance	• Inspections to assess the condition of ecological assets in the bridge underpasses should be conducted annually to ensure they operate as intended. Frequent inspections are necessary to ensure structures are performing their ecological function. • Any significant failures (those that prevent use by target species) should be rectified as soon as possible to ensure operational performance is not compromised. Ecological failure of a structure could result in loss of ecological connectivity for potentially long periods of time, which could have severe consequences for local fauna. • Inspections should be conducted by an appropriately qualified person experienced in the design, assessment, and function of Fauna Sensitive Transport Infrastructure Delivery (FSTID) (Chapter 8).
Monitoring and performance evaluation	• Develop and implement a performance evaluation plan, in accordance with Chapter 3.

Figure 3(a) – Fencing should be attached closely to crossing structures and other permanent structures to prevent animals squeezing past

Source: © Rodney van der Ree, WSP

Table 3(b) – Recommended optimal minimum size (H x W) of the 'terrestrial wildlife zone' in bridge underpasses

TARGET SPECIES	2 - LANE ROADS	4 – 6 LANE ROADS[3]	>8 LANE ROADS
Eastern grey kangaroo	1.8 m x 1.2 m	2.1 m x 1.2 m	2.4 m x 1.5 m
Wallaby	1.5 m x 1.2 m	1.5 m x 1.2 m	1.8 m x 1.5 m
Koala[3]	1.2 m x 1.2 m 2.4 m x 1.5 m if with timber rail	1.2 m x 1.2 m 2.4 m x 1.5 m if with timber rail	1.2 m x 1.2 m 2.7 m x 1.5 m if with timber rail
Wetland walking birds	1.5 m	1.8 m	2.1 m
Possums[3]	2.4 m for timber rail	2.4 m for timber rail	2.4 m for timber rail
Microbats[4]	1.8 m	2.4 m	2.7 m
Small mammals, reptiles	0.6 m x 0.6 m	1.2 m x 1.2 m	1.5 m x 1.2 m

[1] All underpasses should be as large (H x W) and as short (L) as possible, and the maximum size that can fit into the design of the project. Minimum dimensions of retrofitted bridge underpasses (i.e. existing bridge underpasses adapted for use by fauna) may be smaller than those identified for new bridge underpasses – consult a species expert for advice.

[2] Width refers just to the terrestrial wildlife zone, which is the area that terrestrial species will be moving along. The width of the overall bridge (i.e. from abutment to abutment) will be greater, and is assumed to be at least 4-5 metres.

[3] Koalas and possums can move along the ground, however, are at increased risk of predator attack. Where possible, timber rails should be installed to minimise this risk for koalas, possums and small mammals – more research needed.

[4] These dimensions apply to bats adapted to flight and foraging in cluttered airspace as well as cave-roosting bats. High-flying microbats are likely to require underpasses larger than 5 x 5 m. More research on use of underpasses for movement by microbats is urgently needed.

Figure 3(b) – Bridge underpass at the Richmond River on the Pacific Highway, northern New South Wales (left), and Bridge underpass with wide terrestrial fauna zone and koala log rail (right).

Source: © Rodney van der Ree, WSP

Figure 3(c) – Bridge underpass in The Netherlands, with rock gabion wall for reptile movement (left), and Bridge underpass on the Calder Freeway, Victoria, showing terrestrial fauna zone adjacent to a secondary road (right).

Source: © Rodney van der Ree, WSP

4 Culverts

Culverts are square, round, or arched structures that permit the movement of fauna, water, and/or stock and people under transport infrastructure. Culverts are typically used for water flow where transport infrastructure cross drainage lines and flood zones.

Culverts are effective crossing structures for a smaller range of fauna than bridge underpasses, and thus bridge underpasses should be used instead of culverts whenever fauna movement is a high priority.

There are a range of culvert types and functions and they should be designed specifically for the needs and requirements of the target species (Table 4).

Table 4 – Summary of the types of fauna culverts and their primary and secondary function

CULVERT TYPE	PRIMARY FUNCTION	SECONDARY FUNCTION	NOTES
Terrestrial fauna culvert (Section 4.1)	Movement of terrestrial fauna	Drainage, movement of people or stock	Use by terrestrial fauna is always a priority
Aquatic culvert (Section 4.2)	Movement of aquatic fauna and drainage	Terrestrial species during no or low flow conditions	Use by aquatic fauna and drainage is always a priority
Amphibian culvert (Section 4.3)	Movement of amphibians	Drainage often achieved	Use by amphibians is always the priority
Multi-use culvert (Section 4.4)	Equal priority to movement of fauna and drainage, people, stock etc		Difficult to achieve effective movement of fauna and other uses.
Incidental-use culvert (Section 4.5)	Drainage, movement of people or stock	Movement of fauna	Minor adjustment to culverts can allow incidental use by fauna in situations where fauna movement is helpful but not essential.

4.1 Terrestrial fauna culvert

Terrestrial fauna culverts are typically box-shaped concrete culverts whose primary function is the movement of land-dwelling species under transport infrastructure. Depending on the design, terrestrial fauna culverts may also:

- Permit movement of certain birds, bat, and aquatic species.
- Allow for drainage.

The placement, design, and management of terrestrial fauna culverts should always be optimised for use by terrestrial fauna. Multi-use culverts (single culverts or an array of multiple culverts) prioritise the movement of fauna and other purposes (most typically water) and are described in Section 4.4

Box culverts are preferred over arch and pipe culverts for facilitating fauna connectivity because they have horizontal floors, larger openings, require less cover, and can be made wider. Pipes have smaller openings compared to box culverts of the same height and curved floors, both of which may deter some species, and should only be used where box culverts are not feasible. For example, pipe culverts are quicker and easier to install on existing transport infrastructure than box culverts and thus may be preferred for constructability reasons.

Culverts are most cost-effective where the transport infrastructure is already on fill but there may be sufficient justification to raise the grade level of transport infrastructure to accommodate a culvert underpass.

The size of a terrestrial fauna culvert is primarily determined by the requirements of the target species of fauna. It is always better to install larger culverts than the minimum required for the target species (see Table 3(b)) because most studies evaluating the effectiveness of underpasses from Australia and around the world indicate that larger (tall and wide) and shorter (length) underpasses are better than those that are smaller and longer [10].

Table 4.1(a) – Design considerations for terrestrial fauna culverts

ASPECT	DESIGN CONSIDERATIONS
Target species	• Proven for most terrestrial fauna, including macropods, koala, small terrestrial mammals, and reptiles. • Dry culverts may be incidentally used by some amphibian species; however, they are not the preferred and recommended structure type for amphibians. Use an amphibian culvert instead (Section 4.3). • If large enough and with appropriate features or furniture, target species can include arboreal species, birds, and microbats.
Design, dimensions and construction materials	• Terrestrial culverts should be as wide and tall as possible. This is best achieved using square or rectangular culverts (i.e. box culverts or slab-linked box-culverts). Pipe culverts are not recommended as culverts dedicated to fauna movement. • The minimum height and width requirements for new and retrofitted terrestrial fauna culverts are specified in Table 4.1(b). • Culverts must be straight and as short as possible, allowing unobstructed views to the other side. • The base should be as natural as possible, such as soil or mulch, or as close as possible to the substrate at the location of the culvert. Where possible, use culverts without a concrete base. • Implement design or structural features to allow the ingress of natural light and airflow. Lack of light may create a behavioural barrier to the movement of fauna. Light requirements will be dependent on the height and length of the structure, along with the specific requirements of the species and expert advice should be sought. Natural light levels can be achieved by: – Separate carriageways: Build each carriageway or railway track onto two separated structures with space between them to allow light and water to reach the ground and improve rates of use by fauna through facilitating the growth of vegetation. Install fauna fencing between the two carriageways or tracks to prevent fauna from accessing the road or railway via the centre median. Ensure any rain or flood water that enters via the median can drain away. – Light wells: Light wells or microclimate vents (i.e. grated lids) can be installed from the median into the culvert below to allow the ingress of natural light. These should be a minimum 1 m x 1 m in size, be located adjacent to kerb and channel as well as in the centre median, if applicable, and where possible should be less than 10 metres apart from each other. Light wells should be built higher than the surrounding ground and should never be used for drainage. Ensure any rain or flood water that enters via the light well can drain away. – Light wells in the road or railway should be avoided because of traffic noise and disturbance affecting usage. This is particularly relevant for high-speed or high-volume roads and trials should be undertaken prior to implementing.

[10] (Jensen et al. 2023)

<table>
<tr><th>ASPECT</th><th>DESIGN CONSIDERATIONS</th></tr>
<tr><td>Inundation and dry passage</td><td>

The culvert should remain dry year-round, ideally set above the 1:10 year flood level. The culvert should be free draining to prevent ponding of water.
If the culvert cannot be set above the 1:10 year flood level or is likely to be inundated during flood events, an alternative dry passage option for terrestrial fauna should be provided. Dry passage requirements:

Can be a ledge, shelf, or alternative structure that provides equivalent dry passage, installed on both outer walls of the culvert or culvert array.
Must connect to terrestrial habitat at both ends.
Can be made from non-biodegradable material (e.g. concrete) or timber.
Must be a minimum 500 mm wide, ideally 1 m wide subject to hydrological constraints and target species. Minimum 600 mm clearance from the culvert ceiling. Minimum dimensions can accommodate smaller fauna (e.g. koala, echidna) but will not accommodate large fauna (e.g. kangaroo).
Height to be as close to the natural ground level as possible while achieving dry passage most of the time (set above the 1:10 year flood level if practicable).

If the culvert is likely to be inundated more frequently than during flood events (e.g. during base or high flow), install a multi-use culvert. The two outer cells must be set higher than the middle cell which is the focus for water flow. The outer cells must meet terrestrial culvert requirements described in this section.
If culvert is large enough, provide interconnecting logs and or additional refuge poles which provide dry passage and refuge for arboreal species.
</td></tr>
<tr><td>Landscape position and fencing</td><td>

Place terrestrial culverts at known or likely movement pathways and WVC hotspots for the target species (Chapter 5).
The position and spacing of culverts depend on the target species. Culverts for species with a small home range may need to be every few hundred metres, while culverts for species with larger home ranges may need to be every few kilometres.
Avoid or where possible re-design or remove potential barriers that may limit access to the culvert, such as adjacent fences, roads, or railways.
Avoid drainage channels that cross culvert entrances. Where required, ensure they don’t obstruct fauna movement by minimising water depth and period of inundation or avoid through use of underground pipes.
Install fencing to funnel the target species to the culvert wherever there is a risk that the target species may access the road. The length of fencing is site- and species-dependent (Section 13).

Fencing needs to tie into the top of the culvert to minimise debris becoming lodged in the fencing and obstructing the flow of water.
Wire-mesh size and height must be adapted to prohibit species from getting within road corridor.

</td></tr>
<tr><td>Landscaping and vegetation</td><td>

Erosion and scour protection at culvert entrances that uses large rocks can inhibit the movement of terrestrial fauna. Where erosion and scour protection is required, use concrete or small rocks where possible.
Vegetation should be planted at the entrance of culverts to encourage fauna, use Section 16.2.
Vegetation should be suitable for the target species and other species where possible, while maintaining access to and view of entrance and exit of culvert.
</td></tr>
</table>

ASPECT	DESIGN CONSIDERATIONS
Furniture and enhancements to encourage use and reduce the risk of predation	• Fauna furniture should be installed at the entrance and along the length of the structure. Fauna furniture can be a combination of artificial shelters and natural features that suit the target species (e.g. logs, rocks, wood piles) to provide shelter from predators and improve habitat suitability. Furniture can be installed on the ground, attached to walls, or built into the structure itself (e.g. bat roosts built into culverts). • There is limited direct research on the use and effectiveness of furniture in crossing structures[11]. Nevertheless, fauna require habitat and any improvement in habitat quality and protection from predators is recommended. Refer to Section 16.5 for more details. • Align furniture along one side of the structure to retain line-of sight views from end to end. • Use a combination of wooden and non-biodegradable artificial shelters, in accordance with Section 16.7. If future access within the structure is likely to be restricted, with limited ability to replace or maintain fauna furniture, use only non-biodegradable furniture. • With sufficient clearance, culverts can include additional structures to provide alternative pathways and allow fauna to avoid predators. – Horizontal logs and rails at ground level for small mammals or elevated for arboreal mammals and koala (Section 16.8). – Refuge poles with resting platforms to provide koalas refuge from predators (Section 16.8).
Lighting	• Where possible, avoid artificial lighting within 100 m of culvert entrances. • Where lighting is required to meet safety standards (Section 19.5).
Maintenance	• Inspections to assess the structural integrity of culverts should be conducted at the same frequency as for culverts described in departmental guide. • Inspections to assess the condition of ecological assets in the culvert should be conducted annually to ensure they operate as intended. Frequent inspections are necessary to ensure structures are performing their ecological function. During periods of high vegetation growth more frequent inspections may be required to ensure that weeds do not impact function. • Any significant failures (those that prevent use by target species) should be rectified as soon as possible to ensure operational performance is not compromised. Ecological failure of a structure could result in loss of ecological connectivity for potentially long periods of time, which could have severe consequences for local fauna. • Inspections should be conducted by an appropriately qualified person experienced in the design, assessment, and function of FSTID (Chapter 8). • Ensure furniture is present and in good condition. Ensure vegetation and/or silt at entrance to and within structure doesn't impede sight lines or movement.
Monitoring and performance evaluation	• Develop and implement a performance evaluation plan, in accordance with Chapter 7.

[11] (but see Goldingay et al. 2018a)

Table 4.1(b) – Recommended optimal minimum size (H x W) of new[1] terrestrial fauna culverts

TARGET SPECIES	2 lane roads	4-6 lane roads	>8 lane roads
Eastern grey kangaroo	2.1 m x 2.4 m	2.4 m x 2.4 m	2.7 m x 2.7 m
Wallaby	1.5 m x 2.4 m	1.8 m x 2.4 m	2.4 m x 2.4 m
Koala[4]	2.4 m x 2.4 m with timber rail 1.2 m x 1.2 m without timber rail	2.4 m x 2.4 m with timber rail 1.8 m x 1.8 m without timber rail	3.0 m x 3.0 m with timber rail 2.4 m x 2.4 m without timber rail
Wetland walking birds	1.2 m x 2.4 m	1.8 m x 2.4 mm	1.8m x 3.0 m
Possums[4]	2.4 m x 2.4 m	3.0 m x 2.4 m	3.0 m x 2.4 m
Microbats[5]	1.8 m x 2.4 m	2.4 m x 2.4 m	2.7 m x 2.7 m
Small mammals, reptiles	0.6 m x 2.4 m	1.2 m x 2.4 m	1.5 m x 2.4 m

[1] All new culverts should be as large (H x W) and as short as possible, and the maximum size that can fit into the design of the project (that is, do not install a 1.2 metre high culvert into a 3 metre embankment – install a 2.7 metre high culvert instead). Minimum dimensions of retrofitted culvert (that is, existing culverts adapted for use by fauna) may be smaller than those identified for new culverts – consult a species expert for advice.

[2] Culvert width should always be the maximum size possible, as the cost of increasing culvert width vs increasing culvert height is relatively minor.

[3] Culvert dimensions for a single carriageway on a dual carriageway road should match the minimum size for the total number of lanes on both carriageways unless the median is wide and fully open. Enclosed medians on dual-carriageway roads should include a grated light well.

[4] Koalas and possums can move along the ground, however, are at increased risk of predator attack. Where possible, timber rails should be installed.

[5] These dimensions apply to microbats adapted to flight and foraging in cluttered airspace as well as cave-roosting bats. High-flying microbats are unlikely to use culverts and are likely to require underpasses larger than 5 x 5 metres. More research on use of culverts and underpasses for movement by microbats is needed.

Figure 4.1 – 3.0 x 3.0 metre box culvert on Pacific Highway, Woolgoolga to Ballina (left), and 2.4 x 2.4 metre box culvert on Calder Freeway, central Victoria (right)

Source: © Rodney van der Ree, WSP

Case Study 6.1 – Quantifying and confirming the population-level benefit of wildlife crossing structures

There are very few published studies that have proven a population level benefit from the implementation of mitigation measures. One notable example relates to Australia's only hibernating marsupial, the mountain pygmy possum (*Burramys parvus*), a cryptic species that is restricted to alpine and subalpine areas on the highest mountains of Victoria and New South Wales[12].

The mountain pygmy possum lives on the ground among rock screes and boulder fields that have accumulated below mountain peaks. In Victoria, the species displays species segregation of the sexes during the non-breeding season. Adult females remain sedentary throughout the year (typically in high-quality, high-altitude areas) while adult males seasonally disperse into the female territory for the purpose of breeding before departing shortly after mating. This social organisation is integral to the species survival because the departure of males from the breeding site reduces competition for food, allowing females to raise young and increase their body weight before hibernation.

Mount Higginbotham in Victoria is home to more than 50% of the world population of the species. However, the development of the Mount Hotham ski resort and associated road (i.e. Alpine Way) fragmented habitat and inhibited the seasonal dispersal of males to and from the breeding area. The result was an increase in population density and altered sex ratios in the female-dominated territory, and reduced overwinter survival rates.

In 1985, habitat connectivity in the area was restored either side of Alpine Way. Two rock-lined tunnels under the road were constructed, along with a 60 metre-long corridor of basalt rock. These structures effectively re-connected areas of breeding habitat up-slope with areas of habitat down-slope. Within just two weeks of their construction, male possums were observed using the scree corridor and tunnels for dispersal. The result was an increase in overwinter survival rates and a reversion back to the population's natural structure.

However, despite the success of the corridor and tunnels in restoring connectivity, a population viability analysis suggested that the mitigation techniques did not completely remove the negative effects associated with the development of the road. Even after mitigation, the median population size of females was predicted to be 15% lower than if the road had not been constructed. Such findings highlight the need to consider population viability when measuring the success of mitigation measures, especially when concerning such rare and endangered species.

[12] (Mansergh and Scotts 1989, van der Ree et al. 2009)

4.2 Aquatic culvert

The Accepted Development Requirements (ADR) for operational work that is constructing or raising waterway barrier works[13] includes extensive details on minimum standards for design features of waterway crossings in different mapped waterways (refer to the spatial data layer Queensland waterways for waterway barrier works).

The guidelines and suggested specifications that apply to fish passage in this manual must also comply with the ADR (and potentially other guidelines and any subsequent updates and revisions). Therefore, proponents should adopt whichever design, dimension, or other specification achieves the better outcome for:

- waterway health and function and
- fish passage.

Aquatic culverts are designed specifically to accommodate passage of fish and other aquatic species and have been installed widely across Australia and internationally. Bridge underpasses are more effective than culverts for fish (Chapter 19) because the waterway channel can be retained in it is natural state, with little to no modifications to the channel, bed, velocity, etc. Where bridge underpasses are not feasible, well-designed culverts can also be effective.

Most research on the design, use, and effectiveness of fish passages has been conducted overseas, and more peer-reviewed published research in Australia and Queensland is needed. Despite the paucity of local research, the DAF guidelines to keep waterways as natural as possible will generally work for fish.

Expert fish ecologists should always be consulted when designing culverts or other fish passage structures (e.g. fishway, Section 5).

The designs of aquatic culverts are described in Table 4.2 and are:

- Site specific, including topography, water volume, water velocity, flood regime, channel profile, stream order, etc[14].
- Dependent on the swimming behaviour of the target species, including swimming speed, body size, burst or sustained swimming, etc[15].

[13] (DAF 2018)
[14] (Shiau et al. 2020)
[15] (Shiau et al. 2020)

Table 4.2 – Design considerations for aquatic culverts

ASPECT	DESIGN CONSIDERATIONS
Target species	• Proven for fish, semi-aquatic mammals, semi-aquatic reptiles, and macroinvertebrates; likely to be effective for many highly aquatic frogs.
Design, dimensions and construction materials	• Advice from an experienced fish ecologist should be sought when designing aquatic culverts for fish passage. • Bridges are the preferred crossing structure for aquatic species. However, if a bridge is not feasible then a box culvert is the next preferred option. A box culvert is more effectively integrated with natural channels and provides more flexibility in design to meet the fish passage requirements than pipe culverts. Large bottomless and/or buried box culverts are preferred for fish passage. • Pipe culverts are the least preferred option as they can be restrictive in natural flows, turbulent in velocity and are prone to perched exits. Also, a much larger pipe diameter is necessary for pipe culverts to meet the bed sediment and flow requirements of an aquatic culvert. Pipe culverts can be used (or retrofitted if already installed and seeking to improve conditions for aquatic fauna) but require additional considerations to manage velocities and access by fish. • On each project, investigate feasibility of replacing small culverts with larger culverts and replacing pipe culverts with box culverts. • Where possible, one large culvert should be used rather than multiple small culverts. If multiple culverts are required: – Use few large culverts rather than numerous small culverts. – Minimum culvert width is 600 mm. – One of the culverts must directly align with the low flow channel to ensure suitable depth of water during base flow periods and that the low flow channel is not obstructed). • The culvert or culvert array should be equally as wide as the main channel width, with a minimum height of 1.2 m, and must meet the following height and vertical position requirements: – Minimum height of 600 mm above base flow conditions. – Water levels in the culvert should match those in the adjacent waterway. – Set at 300 mm below bed level to allow for natural accumulation of bed sediments and reduce the likelihood of perched entrances forming. This is most easily achieved with an array of culverts where some culverts are set at ground level to enable effective inspections and others set deeper to allow for sediment deposition. Culverts should be as short as possible. If a culvert exceeds six metres, then baffles or other roughening techniques should be applied. The longer the culvert the higher the water velocity and laminar flow (water flow without turbulence), which can make a culvert difficult for fish to navigate. • Culverts should be as short as possible. If a culvert exceeds 6 m, then baffles or other roughening techniques should be applied. The longer the culvert the higher the water velocity and laminar flow (water flow without turbulence), which can make a culvert difficult for fish to navigate. • Suitable flow rates are generally considered to be 0.3 m/s for small- to medium-sized fish. If flow rate exceeds 0.3 m/s baffles or other roughening techniques should be applied. • Culverts are to have no slope or to be installed to match the bed gradient where the culvert is recessed into the bed sediments. • Headwalls, tail walls, or wingwalls should be at 90° (perpendicular) to the culvert. Diagonal walls produce poor hydraulics for fish passage. • Sediment control debris deflector walls can be used to reduce blockages while reducing maintenance costs.

ASPECT	DESIGN CONSIDERATIONS
	• Design or structural features to allow the ingress of natural light and airflow should be implemented. Lack of light within an enclosed structure may create a behavioural barrier. Light requirements will be dependent on the height and length of the structure, along with the specific requirements of the species, and expert advice is necessary to determine the importance of modifying design to consider light needs. Two options to allow the ingress of natural light into culverts are: – Separate carriageways: Build each carriageway onto two separated structures with space between the carriageways (ideally 5 m). This will allow light and water to reach the ground and improve rates of use by fauna through facilitating the growth of vegetation. Install fauna fencing between the two carriageways to prevent fauna from accessing the road and median strip from below. Ensure any rain or flood water that enters via the median can drain away. – Light wells: Light wells or microclimate vents (i.e. with grated lids) can be installed from the median into the culvert below to allow the ingress of natural light. These should be a minimum 1 m x 1 m in size, be located adjacent to kerb and channel as well as in the centre median if applicable, and where possible should be less than 10 m apart from each other. The base of dedicated fauna culverts should be as natural as possible, such as soil or mulch. Where possible, use culverts without a concrete base.
Inundation and dry passage	• If the aquatic culvert is in a location that is likely to be highly trafficked by terrestrial fauna, install a multi-use culvert with the two outer cells set higher than the middle cell which is the focus for water flow (Section 4.4). The outer cells should meet terrestrial culvert requirements (Section 4.1).
Landscape position and fencing	• Fencing is not required if the culvert is just for fish. Fencing is required if turtles, rakali, and/or platypus are likely to be in waterway. The length of fencing is site- and species-dependent, refer to Section 13 for guidance. • Fencing needs to tie into the top of the culvert to minimise debris becoming lodged in the fencing and obstructing the flow of water.
Landscaping and vegetation	• Any channel Section that has been diverted, reprofiled, and/or created must be rebuilt to be as natural as possible allowing for natural features such as vegetation, rocks, and leafy woody debris to be present. • Banks upstream and downstream disturbed as part of the works should be reprofiled to be consistent with existing and banks must be revegetated with locally appropriate riparian vegetation. If existing banks are highly disturbed, then reprofile and revegetate to improve conditions. • If erosion or scour control is necessary: – Minimise scour protection that can create traps or barriers for fish movement during low flow periods. If scour protection is required, use concrete or small rocks. – Ensure there is a clear passage end-to-end, with no pools or puddles that can entrap fish. – Any very large rocks should be embedded into the channel bed to prevent water pooling beneath and trapping fish. – Scour protection should be placed at or below bed level and not extend more than 20 m upstream and/or downstream of the structure. Scouring and perching at the entrance or exit of the culvert must be avoided.
Furniture and enhancements to encourage use	**Enhancements for fish:** • Baffles: Vertical and/or horizontal baffles can be installed on one or both side walls of the culvert (and/or on outer culverts on the walls closest to the river banks) and the culvert invert to aid the creation of eddies (circular current of water) and act as energy dissipators, slowing water velocity. They also change the flow pattern in the vicinity of the culvert, creating zones of fast- and slow-

ASPECT	DESIGN CONSIDERATIONS
	moving water. This allows fish to use short bursts of energy while allowing periods of rest, refer to Figure 4.2(a) for example of baffles. • Baffles can be retrofitted to existing pipe culverts where it is not feasible to replace the pipe with a box culvert. • Fishways can be installed when culverts or other barriers obstruct fish passage (Section 5). • Rock ramps: In Australia, rock ramps are commonly used to facilitate fish movements and are a good tool for slowing water velocity down and encouraging fish movement through culverts. Rock ramps are constructed by placing large rocks or pre-cast concrete cones [16] within streams to form a fishway type system. They cater for a variety of fish behaviours and movement patterns and allow migration even during relatively low-flow events. Gradient and design are determined by maximum swimming speeds and duration of high-speed swimming bursts of the target species of fish. • Wetlands, refuge pools, or plunge pools: A 0.5 m high, downstream sloped (30°) water retention end-sill (usually concrete) can be considered for raising the tailwater, thereby reducing turbulence and providing a refuge / plunge pool. • Large woody debris: Large woody debris (logs, large branches) can be an added benefit by creating suitable habitat and encourage species to access and utilise the culvert (must consider placement, and risk of woody debris becoming an obstruction). **Enhancements for amphibians, semi-aquatic mammals and terrestrial fauna:** • Aquatic culverts can be enhanced for amphibians and semi-aquatic mammals by including features described in Table 4.3. • Aquatic culverts can potentially be enhanced for terrestrial fauna by including ledges and shelves described in Table 4.1(a). • Wetland habitat (i.e. frog ponds) can be created at the ends of culverts (Section 6.10).
Lighting	• Where possible, avoid artificial lighting within 100 m of culvert entrances. • Where lighting is required to meet safety standards (Section 19.5).
Maintenance	• • As for terrestrial fauna culverts, refer to Table 4.1(a)
Monitoring and performance evaluation	• Develop and implement a performance evaluation plan, in accordance with Chapter 8.
Construction in waterway considerations	• Refer to Chapter 7
Retrofits of existing culverts	Existing culverts can be retrofitted to improve fish passage conditions by: • Reprofiling the waterway to correct for scouring. • Adding baffles to the inside of the culvert to reduce water velocity. • Modifying upstream to improve flow in to culverts by raising low-flow water levels within culverts. This can also ameliorate issues associated with deep drops or excessively steep rock ramps. • Replacing scoured material from downstream of culverts that has resulted in excessive drops, refer to Figure 4.2(b)

[16] (Stuart and Marsden 2021)

Figure 4.2(a) – Example of aluminium right-angle baffles installed on bankside culvert viewed from upstream

Source: © Andrew Berghuis, Aquatic Biopassage Services

Figure 4.2(b) – Pipe culvert with perched exit under Savages Rd, Brookfield, Queensland

Source: © Laura Dee, WSP

Baffles on the sides of culverts shown in Figure 4.2(a) are a recommended mitigation to maintain or enhance fish passage. The perched culvert shown in Figure 4.2(b) is a barrier to fish passage and is an example of where retrofits could improve the situation.

4.3 Amphibian culvert

Amphibian culverts are specifically designed to facilitate the movement of frogs. They differ from aquatic culverts which are specifically designed for fish and from terrestrial culverts which are primarily designed for terrestrial fauna.

There are very few studies specifically evaluating the characteristics and performance of crossing structures for amphibians in Australia[17]. Consequently, some guidance provided here is from international studies along with knowledge of Queensland amphibians.

Many amphibians are likely to successfully cross narrow roads or those with less traffic; the likelihood of success largely depends on the combination of traffic speed and traffic volume.

Internationally, amphibian culverts that are wider and shorter are most effective at facilitating crossings, as well as those with natural substrates[18]. Increasing the number of culverts in an array and hence the available area for passage, can also increase effectiveness[19]. Fencing that directs amphibians towards crossings is necessary to reduce road mortality[20]. Ensuring permanent or near-permanent inundation of the base of one or more culverts is also important for passage effectiveness, particularly for highly aquatic amphibians, such as the striped marsh frog (*Limnodynastes peronii*) and Dahl's aquatic frog (*Litoria dahlii*)[21].

The detailed design elements for amphibian culverts described below align as far as possible with the *Growling Grass Frog Habitat Design Standards*[22], as well as a successful culvert system design for this species[23]. Many of these design elements can also be incorporated into terrestrial and aquatic culverts to better facilitate amphibian movement.

Table 4.3 – Design considerations for amphibian culverts

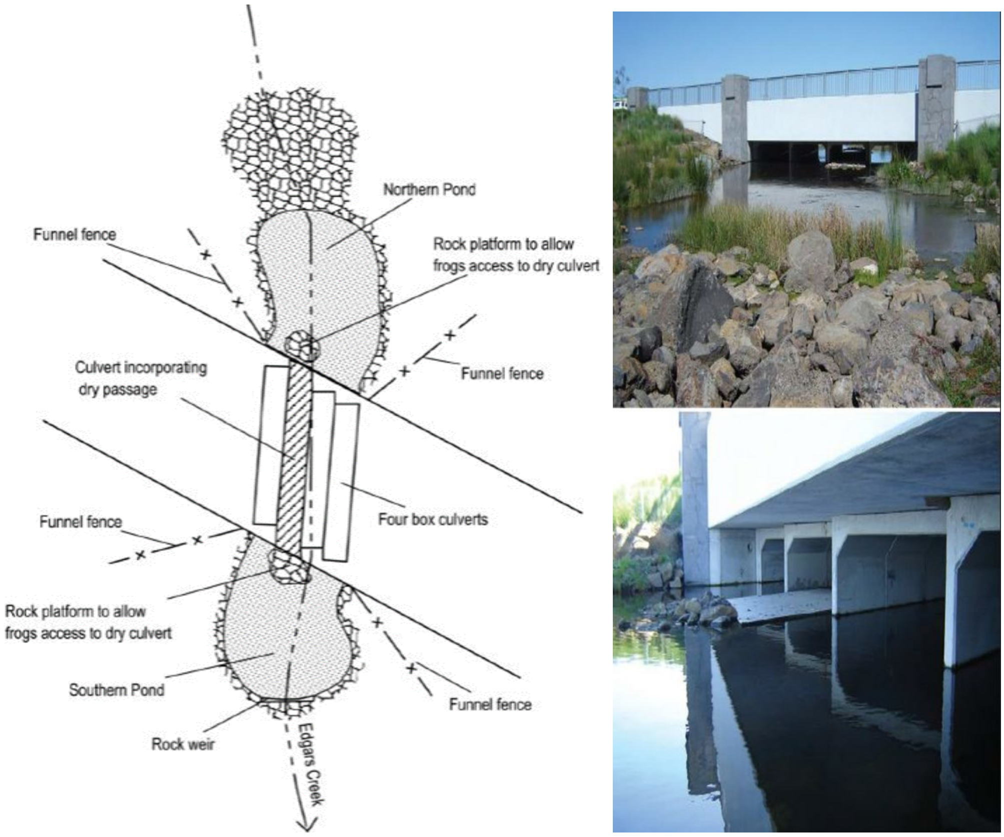
ASPECT	DESIGN CONSIDERATIONS
Target species	• Proven use for growling grass frog in Victoria and likely effective for other amphibian species. • Effectiveness likely to be higher when combined with wetland habitat at either end of the culvert systems.
Design, dimensions and construction materials	• Bridges over a waterway are the preferred crossing structure for amphibians because the waterway is the least modified and can include natural channel, rocks, vegetation, and other furniture. • A culvert system should be used where a bridge underpass is not feasible. • Amphibian culverts should be as wide and tall as possible. This is best achieved using square or rectangular culverts (i.e. box culverts or slab – linked box - culverts). Pipe culverts are not suitable as amphibian culverts. • Amphibian culvert design requirements: – Culvert systems consist of an array of up to four culverts, with total width depending on target species and hydrological requirements. – Each culvert should have minimum 1 m height and 3 m width. Preferably, length should not exceed 30-35 m. Longer culverts should include light wells or gaps in the median. – Must remain inundated year-round and include a dry passage option. – Minimum of 600 mm airspace must be maintained between the normal water surface and culvert ceiling.

[17] (Taylor and Goldingay 2010, Hamer et al. 2014, Smith et al. 2020)
[18] (Lesbarreres et al. 2004, Woltz et al. 2008)
[19] (Dodd et al. 2004)
[20] (Jarvis et al. 2019)
[21] (Koehler and Gilmore 2014, Gleeson et al. 2019)
[22] (DELWP 2017)
[23] (Koehler and Gilmore 2014)

	• Culverts must be straight and as short as possible and should allow unobstructed views to the other side. • The base of amphibian culverts should ideally be a natural surface, i.e. bed sediments for inundated culverts and soil with embedded rocks for dry culverts. • At least some amphibian species are likely to benefit from allowing natural light and moisture to penetrate the culvert. Two options to allow the ingress of natural light into culverts are: – Separate carriageways: Build each carriageway onto two separated structures with space between the carriageways (ideally 5 m or more). This will allow light and water to reach the ground and improve usage by fauna through more favourable microclimate conditions and by facilitating the growth of vegetation. Install fauna fencing between the two carriageways to prevent fauna from accessing the road and median strip from below. Ensure any rain or flood water that enters via the median can drain away. – Light wells: Light wells or microclimate vents (i.e. with grated lids) can be installed from the median into the culvert below to allow the ingress of natural light. These should be a minimum 1 m x 1 m in size, be located adjacent to kerb and channel as well as in the centre median, if applicable, and where possible should be less than 10 m apart from each other.
Inundation and dry passage	• Amphibian culverts must remain inundated when the waterway has water in it, ensuring a minimum of approximately 200-300 millimetres of water depth during base flow events. • A supply of suitable water (e.g. treated stormwater, directed overland flows from vegetated areas) should be identified as part of the design. Water supply options must include fish exclusion measures to prevent the introduction of predatory exotic fish such as Eastern gambusia (*Gambusia holbrooki*) into frog ponds. • Amphibian culverts should include elevated dry areas that provide shelter and resting opportunities for amphibians (e.g. rock gabion or rock platform): – Ideally positioned centrally to the culvert array (i.e. in one of the central culverts). – Must run the full length of the culvert, and slope to the ground or water level at both ends. – Minimum width of 500 mm, and height approximately 100 mm above the base flow or normal water level (ideally set above the 1:10 year flood level). – Rock gabions are a cage or mesh basket filled with rocks to create a small wall. Rocks in the gabion should be between 100 mm to 250 mm in diameter to provide sufficiently sized nooks and crannies for refuge. Gabion baskets present a risk of entrapment to fish and should be filled with smaller-sized sediments from below base-flow levels. – Rock platforms consist of large rocks cemented to the ground. Rocks in the platform may need to be larger than for gabions to resist movement during high flows or to be secured to the base of the culvert (e.g. concreted in). – A dedicated dry culvert may also be required in some instances for certain species. If a dry culvert is required as part of the culvert array, a structure that provides shelter for amphibians must be included for the full length of the culvert (e.g. a rock platform or gabion wall, width approximately 500 mm, and height approximately 300 mm).
Landscape position and fencing	• The position and spacing of culverts depend on the target species. Culverts for species with a small home range may need to be every few hundred metres, while culverts for species with larger home ranges may need to be every few kilometres. • Avoid or where possible re-design or remove potential barriers that may limit access to the culvert, such as adjacent fences, roads, or railways.

	• Place amphibian culverts in proximity to existing wet habitat where possible; metapopulation dynamics (i.e. dispersal and colonisation) will increase the likelihood of successful use of the culverts. • Any channel Section that has been diverted, reprofiled, and/or created must be rebuilt to be as natural as possible allowing for natural features such as vegetation, rocks, and leafy woody debris to be present. • Install fencing to funnel the target species to the culvert wherever there is a risk that the target species may access the road. The length of fencing is site- and species- dependent (Section 13). – Fencing needs to tie into the top of the culvert to minimise debris becoming lodged in the fencing and obstructing the flow of water.
Landscaping and vegetation	• Appropriate vegetation must be planted surrounding the entrance of culverts and around associated habitat ponds to encourage frogs to use the culvert. Vegetation plantings should: – Be designed and shaped to funnel fauna towards the underpass. – Consist of terrestrial and aquatic plant species and use indigenous stock wherever possible. – Consist of the preferred habitat of the target species. – The planting of trees and shrubs should be minimised around culvert entrances and culvert ponds, so as not to shade the water surface — shading reduces water temperatures and potentially facilitates the spread of amphibian chytrid fungus.
Furniture and enhancements to encourage use and reduce the risk of predation	• Where feasible, amphibian culvert systems should have a dedicated frog pond located at either end of the culvert system, to which the inundated culverts are permanently hydrologically connected, except the dry season or during drought. Dedicated frog ponds are not suitable as sediment basin or treatment ponds, due to the risk of pollution impacting frogs. Specific herpetological advice is likely to be required in the design of frog ponds. Refer to Section 16.10, for further details. **Enhancements for terrestrial species:** • Amphibian culverts can potentially be enhanced for terrestrial fauna by including ledges and shelves and/or the addition of multiple cells as described in Table 4.1(a). **Enhancements for fish:** • Amphibian culverts can be enhanced for fish and other aquatic species by including design features described in Table 4.2.
Lighting	• Where possible, avoid artificial lighting within 100 m of culvert entrances. • Where lighting is required to meet safety standards, see Section 19.5
Maintenance	• As for terrestrial fauna culverts, refer to Table 4.1(a)
Monitoring and performance evaluation	• Develop and implement a performance evaluation plan, refer to Chapter 3.

Figure 4.3(a) – Photos and schematic of growling grass frog culvert system in northern Melbourne, Victoria



Source: Koehler and Gilmore (2014)

4.4 Multi-use culvert

Multi-use culverts are specifically designed and managed to allow the movement of fauna as well as people, livestock, or water. Incidental-use culverts, where the primary aim is something other than the movement of fauna, are described in Section 4.5. Multi-use culverts can be cost-effective, however must be planned, designed, and managed to ensure that fauna movement is not compromised. It is not acceptable to label a drainage culvert a multi-use culvert without including specific design features to facilitate the movement of fauna. In other words – incidental-use culverts and standard drainage culverts do not qualify as multi-use culverts because they are not specifically designed to also enable fauna movement.

In most cases, multi-use culverts should be an array of slab-linked box culverts rather than a single cell that caters equally for both fauna and other uses. Multi-cell culverts are usually preferred over a single cell with shelf.

A significant challenge in multi-use culverts is standing water, which often occurs due to poor design, construction and/or maintenance. Culverts that contain permanent water or water for many weeks of the year are less preferred by terrestrial fauna than culverts which are dry or mostly dry for most of the year. The culvert in Figure 4.3(b) is an example of a multi-use culvert however in this example the lack of a low flow channel in the rock apron means that there is still a barrier to fish passage during low flow periods.

Discussion of the type and frequency of multiple uses are given in Section 2.2.

The design of multi-use culverts should be based on the requirements for the multiple uses, with a focus on maximising the benefits for the target species, rather than the other uses. Refer to Table 4.1(a), Table 4.2 and Table 4.3 for details.

Figure 4.3(b) – A multi-cell multi-use culvert array on the Logan Enhancement Project, Brisbane, Queensland. Note that the large rocks may hinder movement of some fauna

Source: © Rodney van der Ree, WSP

Figure 4.3(c) – Single culvert with ledge and rails

Source © Aurecon

4.5 Incidental-use culverts

Incidental-use culverts are primarily designed for other purposes such as drainage or the movement of people or stock and have some modifications to allow occasional or incidental use by fauna. Incidental-use culverts can be of any design – box, arch, or pipe, and single or multi-cells. Incidental-use culverts offer a cost-effective approach to increasing connectivity for fauna when the goal for fauna movement is limited to occasional or incidental use.

The primary consideration with incidental-use culverts is to ask: is it important that this culvert is used by fauna? If the answer is yes – then it should be a terrestrial culvert, an aquatic culvert, or a multi-use culvert. Nevertheless, wherever possible, drainage structures should be designed to also allow incidental movement of fauna using the numerous design considerations outlined for other culvert types.

5 Fishways

Fishways are structures that are typically retrofitted to an existing structure (e.g. culvert crossing to remediate a head loss, or constructed on a new barrier such as a dam or weir that enables the movement of fish and other aquatic organisms past barriers within waterways[24]. Where fishways are retrofitted to existing structures, the removal or upgrade of the barrier that is not providing adequate fish passage should always be considered as the first option.

Water is directed through the fishway to attract the fish to the entrance. Fishways typically contain resting pools to allow fish to rest as they move through the fishway. Some examples of fishways include rock ramp fishways, cone fishways, vertical slot fishways, fish locks and fish lifts.

Table 5 – Design considerations for fishways, elevators, and ramps

ASPECT	DESIGN CONSIDERATIONS
Target species	• Proven for all fish species, macroinvertebrates, and other aquatic and semi-aquatic species (e.g. platypus, turtles).
Design, dimensions and construction materials; Inundation and dry passage	• Design requirements are highly dependent on the target species, the requirements of those species to move, and the space available for the structure. The project will need to consult with a specialist to establish the following: – Hydraulic performance (velocity, turbulence, flow depth, sediment control, debris blockage, and related requirements). – Physical performance (ecological and fish passage objectives). • The structure needs to account for a range of fish that may be small (20-100 mm) to medium and large (100-1400 mm) bodied fish, and a range of hydraulic flows. The requirements will vary dependent on the type and structure used at the specific location. • Additional considerations include areas of rest and refuge within the fishway, the direction of migration, and the flow requirements during these stages. • Minimum depth of water should be maintained while the fishway is functional (0.3-1 m depth). • Refer to [25] and others at Fishways and fish movement.

[24] (Amtstaetter et al. 2017)
[25] (O'Connor et al. 2015, O'Connor et al. 2017a, O'Connor et al. 2017b)

Landscape position and fencing	• Always positioned on waterways. • Fencing not required as targeting fish.
Landscaping and vegetation	• Where possible the channel should be maintained as natural as possible. • Any channel Section that has been diverted, reprofiled, and/or created must be rebuilt to be as natural as possible allowing for natural features such as vegetation, rocks, and leafy woody debris to be present. • Banks upstream and downstream that are disturbed as part of the works should be reprofiled to be consistent with existing and banks must be revegetated with locally appropriate riparian vegetation. • If existing banks are already highly disturbed, then reprofile and revegetate to improve conditions. • Vegetation plantings should: – Follow the locally indigenous Regional Ecosystems and use indigenous stock wherever possible. – Include (where possible) trees that will grow to provide natural shade and reduce sun exposed Section near the concreted structure to help reduce water temperatures. – Match the adjacent vegetation (species and compositional structure) and provide a continuation of the natural landscape. • If erosion or scour control is necessary: – Minimise scour protection that creates trap or barriers to fish movement during low flow periods. If scour protection is required, use concrete or small rocks instead. – Any very large rocks should be embedded into the channel bed to prevent water pooling beneath and trapping fish. – Scour protection should be placed at or below bed level and not extend more than 20 m upstream and or downstream of the structure. Scouring and perching at the entrance or exit of the culvert should be avoided.
Furniture and enhancements to encourage use	• Use natural and locally sourced materials consistent with bed materials where available. • Large woody debris can be an added benefit by creating suitable habitat and encourage species to access and utilise the crossing structures (must consider placement, and risk of woody debris becoming an obstruction).
Lighting	• Where possible, avoid artificial lighting within 100 m of structures. • Where lighting is required to meet safety standards, refer to Section 19.5.
Maintenance	• As for terrestrial fauna culverts, refer to Table 4.1(a). • Fishways should be de-watered annually for a full inspection to assess structural integrity. De-watering should be undertaken to avoid migratory and spawning periods where possible. Site and species requirements should be confirmed prior to any work.
Monitoring and performance evaluation	• Develop and implement a performance evaluation plan, refer to Chapter 3.
Construction in waterway considerations	• Refer to Chapter 7.

Figure 5(a) – Slacks Creek rock ladder and baffles (left), and Slacks Creek baffles (right)

Source: © State of Queensland

Figure 5(b) – Slacks Creek fishway (left), and Reliance Creek fishway (right)

Source: © State of Queensland

6 Vegetated land bridge

Vegetated land bridges are overpasses that facilitate the movement of fauna above transport infrastructure. Land bridges are planted with native vegetation that matches the surrounding ecosystem and habitat and provide a relatively natural pathway for a large suite of fauna species. Land bridges also provide habitat for fauna and facilitate ecosystem processes.

Land bridges are most cost-effectively installed where the transport infrastructure is in a cutting or at grade. Land bridges can be constructed using bridges (Figure 6(a)), bored tunnels and cut and cover tunnels.

There are currently three vegetated land bridges installed on the Pacific Highway in northern New South Wales, three in the suburbs of Brisbane, Queensland, and one in Ellenbrook Western Australia. Additional land bridges are being built in New South Wales and Queensland and being considered elsewhere.

Land bridges in New South Wales and Queensland have been monitored and a diverse suite of taxa regularly use them, including macropods, small mammals, arboreal mammals, birds, reptiles, and invertebrates[26]. The bridges have also been shown to minimise the road effect zone and facilitate activity of and provide habitat continuity for some Australian microbats[27].

Land bridges in Europe have been constructed with irrigated drainage lines to facilitate the movement of amphibians.

Land bridges can be dedicated to fauna movement or combined with movement of people (e.g. walking trail), however little is known about the way in which fauna use is impacted by the presence of people[28]. In the absence of evidence demonstrating the success of co-use crossing structures, land bridges should be dedicated to fauna movement. If pedestrian movement is also required, the use by people should be restricted to low-intensity walking trails, the land bridge should be wide, the two uses physically separated, and no lighting installed. Comprehensive monitoring should be undertaken to evaluate the effects of recreational uses on use by fauna.

To date, vegetated land bridges are the only type of overpass which have shown evidence of use by koalas. Recent evidence shows that koalas use the Compton Road bridge on a frequent and regular basis[29]. A land bridge in Ellenbrook near Perth, WA has recently been used by emus to cross the Tonkin Highway.

[26] (Bond and Jones 2008, Taylor and Goldingay 2010, Jones and Pickvance 2013, McGregor et al. 2015)
[27] (McGregor et al. 2017)
[28] (Van der Grift and van der Ree 2015)
[29] (Darryl Jones, unpublished data)

Table 6 – Design considerations for land bridges

ASPECT	DESIGN CONSIDERATIONS
Target species	• Proven for all groups of terrestrial fauna, including macropods, koala, small terrestrial mammals, reptiles, amphibians, and invertebrates, as well as arboreal species, birds, and bats. • Amphibians will also use land bridges with irrigated waterways[30]. • Land bridges at bored tunnels and cut and cover tunnels permit the movement of all species, as the habitat remains undisturbed (bored tunnel) or is fully rehabilitated (cut and cover tunnel).
Design, dimensions and construction materials	• The bridge should be as wide as possible; minimum optimal width of vegetation that fauna use is 40 m. Narrower bridges (potentially down to 10-20 m wide) may be possible depending on the needs of the target species and species experts should be consulted. Land bridges to facilitate ecosystem connectivity in western Europe are 50-80 m wide[31]. • Soil depth is related to the vegetation type of the target species, with a minimum depth of 1.5 m to 2 m required to support trees. • Approach ramps are gently graded, ideally 5 horizontal:1 vertical. Approaches can be steeper (up to approximately 3:1) depending on target species and where protection of adjacent vegetation and habitat is required. • Approach ramps and bridges can be hourglass- or funnel-shaped to encourage fauna to access and enter the overpass. • Construction method depends on topography (i.e. if road or railway is in a cutting or at grade), whether the road or railway must allow for over-dimensional vehicles, and the length of the span. Construction can include pre-cast concrete arches, bored tunnels, cut and cover tunnels, or concrete bridges. The structure must be able to support the soil (including at times of waterlogging) along with the mature vegetation. • If drainage is required across the entrance to the bridge, it should be connected via a pipe beneath the bridge entrance to minimise disruption to access. If an open swale is required, it should be free draining and not remain inundated for extended periods and/or restrict access to the land bridge. If this not possible, dry access should be provided across the channel.
Landscape position and fencing	• Land bridges are most cost-effective at locations where the transport infrastructure is in a cutting. They can be built where the transport infrastructure is at- or slightly above-grade, however this is more expensive and the approach ramps will extend further, requiring more land and potentially more clearing of adjacent vegetation and habitat. • Land bridges should be built where native vegetation / habitat for the target species occurs (or can be replanted) on both sides of the transport infrastructure. • The spacing of land bridges depends on the home range and movement characteristics of the target species. • Avoid, or where possible re-design or remove, potential barriers that may limit access to the culvert, such as adjacent fences, roads, or railways. • Install fencing to funnel the target species to the bridge wherever there is a risk that the target species may access the road. The length of fencing is site- and species- dependent, refer to Section 13.

[30] Edgar van der Grift, unpub. data.
[31] (IENE 2022)

	• Fauna fencing along the transport infrastructure may not be required if the land bridge offers an attractive alternative to crossing the transport infrastructure elsewhere or where steep or tall abutments that prevent use elsewhere. However, in most cases, fencing is required. • Fauna fencing on the land bridge is required to prevent fauna falling onto the transport infrastructure below. If properly designed, noise and light walls may be effective fauna fencing.
Landscaping and vegetation	• Vegetation must be planted on and leading up to the bridge to encourage fauna to use the structure. In addition: – Allow adjacent vegetation to grow up to and onto the land bridge, providing seamless transition from adjacent habitat to structure. – Include different bands of habitat across the bridge (e.g. one side forested, the other more open grassland) to suit a diversity of target species. • Use noise and light walls on the edge of the land bridge to reduce noise and light from oncoming vehicles. Soil berms can be used but the additional weight they bring should be considered.
Furniture and enhancements to encourage use	• Place artificial shelters (Section 16.7) or natural habitat features (Section 16.5) such as logs, rock jumbles, piles of brush, and woody debris that suit the target species on the bridge to provide natural cover / shelter from predators and improve habitat suitability. Similar materials can be used on the approach to the bridge to prevent unauthorised vehicle access. • Use a combination of wooden and non-biodegradable artificial shelters, in accordance with Section 16.7. • Additional structures can be installed on land bridges to facilitate movement of arboreal mammals: – Canopy bridges, refer to Section 7. – Glider poles, refer to Section 9. – Elevated horizontal logs for arboreal mammals or log rails, refer to Section 16.8. – Refuge poles with resting platforms to provide koalas refuge from predators, refer to Section 16.8. – Horizontal logs for small mammals, refer to Section 16.8. • Shallow waterbodies, wetlands, or frog ponds can be installed on the land bridge and/or the approaches to encourage frogs to move over the structure.
Lighting	• Where possible, avoid artificial lighting within 100 m of land bridge or approach ramps. • Where lighting is required to meet safety standards, refer to Section 19.5.
Maintenance	• As for terrestrial fauna culverts, refer to Table 4.1(a)
Monitoring and performance evaluation	• Develop and implement a performance evaluation plan, in accordance with Chapter 3.

Figure 6(a) – Compton Road land bridge Brisbane (left), and Yelgun land bridge (right) on Pacific Highway

Source: © Rodney van der Ree, WSP

Case Study 6.2 – Maintaining / improving habitat at crossings for several small mammal species.

In this hypothetical case study, road managers are designing a vegetated land bridge for rodents, bandicoots, and wallabies. By considering each species' ecology they find that the smaller-bodied rodent species are more capable of moving rapidly through dense mid and understorey, whereas larger-bodied wallaby species are likely to be impeded by dense mid and understorey. The bandicoot species are known to require both dense understorey for hiding and foraging, and areas of sparse understorey for rapid movement through the landscape. If managers only considered the requirements of the rodent species, they might have chosen to revegetate the area with dense understorey. In this case, the crossing habitat would be suitable for the rodent species but not the bandicoots and wallabies. The managers can maximise the effectiveness of the crossing by considering the specific needs of all the target species. In this case, they can revegetate the crossing with areas of both dense and sparse understorey so that all the target species are more likely to use the habitat and crossing (Figure 6(b) and Figure 6(c)).

Figure 6(b) – Recently constructed vegetated land bridge in France, with zones and plantings for different species of fauna

Source: © Rodney van der Ree, WSP

Figure 6(c) – Land bridge over Hamilton Road, Brisbane, showing zones with tall trees and central zone with shorter grasses for different species of fauna

Source: © Rodney van der Ree, WSP

7 Rope-ladder canopy bridge

A canopy bridge is a structure, usually a rope-ladder design, that connects the canopy of trees together. While typically installed above roads, they can also be installed under road bridges (Section 8) or on vegetated land bridges.

Canopy bridges are used for arboreal mammals (Chapter 14), including the brush-tailed phascogale, common brushtail possum, common ringtail possum, and smaller gliders (e.g. Krefft's glider, sugar glider, and squirrel glider). Occasional use by arboreal reptiles, such as goannas, has been recorded[32]. One study on the Pacific Highway in northern New South Wales detected yellow-bellied gliders (*Petaurus australis*) using one canopy rope bridge[33]. Koalas have never been observed using canopy bridges, including during an almost three-year trial of different types of rope ladders[34] and a six months monitoring program of a single steel gantry near Brisbane[35] (Chapter 13).

Due to safety concerns canopy bridges are not considered a feasible design option for electrified railways. The only acceptable option for electrified railways is either a canopy bridge in conjunction with a land bridge (Section 6) or an under-bridge canopy bridge (Section 8) where the railway is elevated.

There is concern about the risk of interference of canopy bridges with overhead powerlines. To avoid any potential conflict, the powerlines should be placed underground during construction on major transport projects. Where powerlines are unable to be placed underground, install canopy bridges under powerlines with sufficient clearance or use glider poles (only suitable for gliding species). More work is needed to design systems to cross electrified networks.

Table 7 – Design considerations for over road canopy bridge

ASPECT	DESIGN CONSIDERATIONS
Target species	• Proven for arboreal and some semi-arboreal mammals, specifically small gliders (e.g. Krefft's glider, sugar glider, squirrel glider) and possums, antechinus, feathertail glider, phascogale. Potentially suitable for larger gliders (e.g. yellow-bellied glider, greater glider), arboreal reptiles (e.g. goannas and carpet pythons), and amphibians (e.g. green tree frogs) – but more research is needed. • Not suitable for koalas.
Design, dimensions and construction materials	• Canopy bridges should be a 450 mm wide rope ladder or a box design, because they are more stable and less prone to twisting than single strands of rope, as shown in Figure 7(a). • 'Box' designs may enable easier two-way movement by fauna and protection from predators than rope ladder designs, however possums and gliders often walk along the top of the box, reducing the benefit of this extra cost[36]. However, research on use of box-type designs is currently underway in Sydney. • Single rope canopy bridges as show in Figure 7(b) are not preferred as they do not allow for two-way movement across the bridge.

[32] (Soanes et al. 2013, Goldingay and Taylor 2017a, Soanes et al. 2018)
[33] (Geolink 2019)
[34] (Goldingay and Taylor 2017b)
[35] (Jones et al. 2013)
[36] (Bax 2006)

	• Canopy bridges should be as short as possible while connecting large or hollow-bearing trees. Multi-span bridges may be required if the span exceeds 70-80 m. • Clearance above traffic lanes must be minimum height of 8.5 m, ideally more. The total allowance should include at minimum a 2 m buffer in above the minimum clearance on freeways, bringing the minimum height to 10.5 m (AS 5100 *Bridge design*) and allows over-dimensional vehicles to pass. • Clearance above railways must be 2 m above height of tallest train on that track. • Rope ladder: – 12-15 mm diameter rope to be used for the ladder. Rope must be UV stabilized, such as marine-grade silver rope. – Use two steel cables to span the gap, to which the rope ladder is attached with d-shackles. – Steel cables should as taut as possible with minimal sag to minimise sway during wind. – Steel cables should be attached to the cross arm with turnbuckles at both ends to enable tightening. – Ensure the gap between the end of the rope ladder and poles is less than 20 cm and any gaps are covered by feeder ropes in order to improve fauna access. • Support poles: – Support poles for canopy bridges above roads must be treated timber poles. – Support poles for canopy bridges installed under road bridges or on land bridges can be timber poles or existing trees because there is no risk to traffic or pedestrians in case of failure. – Use rough-sawn timber poles where possible and avoid steel poles and smooth timber poles because they are more difficult for animals to climb. – In most situations, poles need to be treated to prevent rot and termite damage. The cross-arm should be non-treated hardwood as this is where fauna will spend most of their time. – Support poles should not be used in medians without trees to prevent fauna climbing down into the median. Support poles can be used in medians with trees that provide habitat for arboreal species. If a support pole is used in a median without trees, a cowl should be fitted to prevent fauna climbing down into the median. – Support poles for canopy bridges which extend above the canopy bridge are unlikely to be sufficiently tall to also act as glider poles as gliders are likely to land on or beneath the canopy bridge. – Poles must be accessible for maintenance and/or installation of cameras or other monitoring equipment. Hard stands can be included at the base of poles and behind guard rails to improve accessibility. – If poles are at risk of vehicle collision, include protective barriers. • Feeder ropes: – The ends of canopy bridges should be tied back with feeder ropes to a minimum of two and preferably three or more large and/or hollow-bearing trees to increase access by fauna. Single-strand feeder ropes should never span clearings where there is a risk of mortality if fauna fall off. In these situations, extend the rope ladder across the road or other dangerous setting. – 40 mm diameter ropes to be used for the feeder ropes. Rope must be UV stabilized, such as marine-grade silver rope.

	• Identify important access trees adjacent to the road or railway during detailed planning and design and protect them during construction. • Tree planting should be undertaken adjacent to refuge and escape poles so that this vegetation will eventually replace the infrastructure, improving both habitat values and connectivity.
Landscape position and fencing	• Canopy bridges should be built wherever preferred habitat for the target species occurs or can be replanted on both sides of the road or railway. • The position and spacing of canopy bridges depends on the target species. Bridges for species with a small home range may need to be every few hundred metres, while bridges for species with larger home ranges may need to be every few kilometres. • Install multiple canopy bridges (potentially including glider poles) because rates of use can vary significantly from structure to structure. • It is very difficult to build effective fences for all species of arboreal mammal. Therefore, canopy bridges should be installed in high quality habitat, along existing corridors, or movement paths and at natural pinch points. • If there is fencing for specific arboreal mammals, the poles and stay wires should be placed behind fauna proof fencing to prevent fauna moving into the road or railway.
Landscaping and vegetation	• Additional poles, canopy bridge and/or tree planting may be required to connect the canopy bridge to adjacent vegetation. • If insufficient vegetation is present, vegetation must be planted to encourage fauna to use the canopy bridge, in accordance with Section 16.1.
Furniture and enhancements to encourage use	• Include a metal predator shield at the top of the pole to provide protection from aerial predators. The shield is typically a circular galvanised metal plate, approximately 900 mm diameter and positioned at least 500 mm above where the canopy bridge is connected to the support pole, ensuring it doesn’t compromise function of the canopy bridge. • Include open-ended lengths of 100-150 mm diameter UPVC pipe (or equivalent), approximately 400 mm in length, installed horizontally on the support poles and at 7-10 m intervals along rope ladder as escape or temporary refuge sites. Further research is required to clarify effectiveness.
Lighting	• Where possible, avoid artificial lighting within 100 m of canopy bridges or feeder ropes. • Where lighting is required to meet safety standards, refer to Section 19.5.

Maintenance	• Canopy bridges (particularly pole and rope components) should be inspected annually. The ropes (ladder and feeder ropes) must be checked for deterioration and failure (Figure 7(e), Figure 7(f)). • The rope ladder must be tensioned to ensure minimum clearance above the road is maintained and to reduce sway. Maximum deflection over a 50 m span shouldn't exceed 1 m. Consult an engineer for detailed design. The first two years are particularly important to deal with sagging by tightening. • Foliage from trees that grows around and through the ends of canopy bridges facilitates access by fauna and this vegetation should be allowed to grow. However, large branches that lean on the rope bridge must be pruned to reduce stress and loading on the bridge. • Foliage in centre medians that are not designed to provide habitat for arboreal species should be pruned and maintained to discourage fauna from accessing the median habitat. However, if the median is designed to provide habitat, foliage should be allowed to grow near the bridge. • Any significant failures (those that prevent use by target species) should be rectified as soon as possible to ensure operational performance is not compromised. Ecological failure of a structure could result in loss of ecological connectivity for potentially long periods of time, which could have severe consequences for local fauna. • Inspections should be conducted by an appropriately qualified person experienced in the design, assessment, and function of FSTID (Chapter 8).
Monitoring and performance evaluation	• Develop and implement a performance evaluation plan, in accordance with Chapter 3.

Figure 7(a) – Rope ladder canopy bridge with a 70 metre span across the Hume Freeway, Victoria

Source: © Rodney van der Ree, WSP

Figure 7(b) – Single-rope canopy bridge on the shared-use land bridge over Hamilton Rd, Brisbane

Source: © Rodney van der Ree, WSP

Figure 7(c) – Steel gantry for koalas across Burbank Rd at Mount Cotton, Brisbane

No koalas were detected using this structure during a 6-month monitoring period.

Source: © Rodney van der Ree, WSP

Figure 7(d) – Rope ladder canopy bridge across railway at Kapooka near Wagga Wagga, NSW

Source: ©Rodney van der Ree, WSP

Figure 7(e) – Degradation of rope ladder canopy bridge due to exposure to UV light

Source: © Rodney van der Ree, WSP

Figure 7(f) – The feeder rope of this canopy bridge has failed because the branch it was connected to has broken off

Source: © Rodney van der Ree, WSP

Figure 7(g) – Close-up of camera on canopy bridge below predator shield

Source: © Rodney van der Ree, WSP

Figure 7(h) – Close-up of timber beams to which the steel cables and rope ladder is attached to

Source: © Allan Richardson, WSP

8 Under-bridge canopy bridge

Canopy rope bridges can be built to pass under the road where there is sufficient clearance underneath. This type of canopy bridge is functionally similar to the above-road canopy bridges and provides safe connectivity for arboreal and semi-arboreal mammals. Under-bridge canopy bridges do not need to be engineered to the same standards as the above-road canopy bridges because the consequences of collapsing are typically lower. Nevertheless, most design features are the same as for above-road canopy bridges because the support poles are typically positioned outside the bridge underpass and exposed to UV, potential predators etc.

Table 8 – Design considerations for under-bridge canopy bridges

ASPECT	DESIGN CONSIDERATIONS
Target species	• Proven for squirrel gliders and Krefft's gliders[37]. • Potentially other arboreal and some semi-arboreal mammals, including other gliders, possums, antechinus, phascogale, and potentially arboreal reptiles, such as goannas, but more research required. • Not suitable for koalas.

[37] (Van der Ree, unpublished data)

ASPECT	DESIGN CONSIDERATIONS
Design, dimensions and construction materials	• As per Section 7. • The canopy bridge is ideally ~1-2 m below the underside of the bridge deck and at least ~5 m above the ground. Therefore, under-bridge canopy bridges are typically not suitable for bridges with less than ~6-7 m clearance. Further research on separation distances is required. • Canopy bridges can be most easily attached to the bridge structure if the attachment points are pre-cast into the bridge deck. Attaching to an existing bridge may be feasible, depending on the type of structure and design. Consult a structural engineer for further details.
Landscape position and fencing	• As per Section 7.
Landscaping and vegetation	• As per Section 7.
Furniture and enhancements to encourage use	• As per Section 7.
Maintenance	• As per Section 7.
Monitoring and performance evaluation	• As per Section 7.

Figure 8(a) – Under-road canopy bridge during camera installation on the Hume Freeway, NSW

Source: © Rodney van der Ree, WSP

Figure 8(b) – Under-road canopy bridge under the Echuca-Moama bridge in NSW

Source: © Rodney van der Ree, WSP

9 Glider poles – over road

Glider poles are timber poles installed on one or both verges of the road or railway and/or in the median and provide a platform for gliders to launch from and/or land on when gliding across the cleared gap. Glider poles can be installed in an array of two or more poles, or they can be used in conjunction with standing trees. Glider poles have been used successfully for numerous glider species across roads in Australia and internationally (Chapter 14)[38]. Greater gliders have also been observed using glider poles on a 30-60 metres wide cleared pipeline easement in Victoria, however it is unclear if successful crossings were made[39]. No greater gliders have been observed using glider poles to cross roads or railways.

There is recent evidence from monitoring conducted at one location on the Oxley Highway in northern NSW which showed that squirrel gliders and sugar gliders preferred to use glider poles over rope bridges, with 12 -18% of detections on pole-pairs and 1% of detections on the rope bridge[40]. The study was based on data from two pairs of poles and one rope bridge and therefore cannot be generalised, because the poles may have been placed in areas of higher quality habitat or be more easily accessed than the rope bridges, thus potentially explaining the variation in rates of use. Similarly, monitoring of the rates of use of glider poles and rope bridges along the Hume Freeway in southern NSW showed variable rates of use of both types of crossing structures[41]. Therefore, a key

[38] (Taylor and Goldingay 2013, Goldingay et al. 2018b, Soanes et al. 2018, Taylor and Rohweder 2020)
[39] (GHD 2017)
[40] (Goldingay et al. 2018a)
[41] (Soanes et al. 2015)

factor influencing rate of use of both glider poles and canopy bridges is their placement in high quality habitat and ease of access from adjacent vegetation.

Glider pole arrays should be designed according to a conservative estimate of the gliding capability of the target species and other gliders that may occur in the area to minimise the risk of fauna vehicle collision. Glide ratios and horizontal distance travelled for a range of glider species is given in Table 9(b). The calculations of glide trajectories are site- and species-specific and must be designed conservatively for each crossing location.

Table 9(a) – Design considerations for above-road glider poles

ASPECT	DESIGN CONSIDERATIONS
Target species	• Proven for squirrel glider, sugar glider, Krefft's glider, mahogany glider (Chapter 14). • Potentially effective for greater gliders, yellow-bellied gliders and feathertail gliders (*Acrobates pygmaeus*), but further research required.
Design, dimensions and construction materials	• Glider poles are installed as an array of two poles (or trees—see next point) on opposite sides of the road or railway, allowing gliders to glide from pole to pole. Wide gaps may require one or more poles in the centre median or between railway tracks. • Use existing large trees (living or dead) rather than poles where possible, by retaining them during construction. Large trees are likely to function better than poles because they are more natural, may contain hollows, and may support invertebrates as food. • Consider the likely standing life of the tree compared to a treated pole. Standing life of dead trees is influenced by tree species, resistance to termite damage and decay, root base, current condition, and position in the landscape (e.g. in swampy vs drier area). • Poles: – The distance between poles depends on species-specific glide trajectory, pole height, pole placement and obstacles. The appropriate distance between poles must be calculated for each installation and based on species- and site-specific factors and the glide angles in. – Table 9(b): Always seek advice from an expert in the implementation of glider poles. However, for early project planning purposes, use the maximum distance between poles in Table 9(b) and assume poles are required in the median. – At a minimum, always use 20 m poles (standard length), which equates to a height above ground of ~17 m. (Table 9(b)). – Poles up to 26 m are available and should be used where required, however they are more expensive to procure and require specialist transportation (i.e. escort services). – Poles must be rough-sawn and not smoothly sanded, to make it easier for gliders to climb. – Poles should always be treated to prevent rot and termite damage. – Protective crash barriers should be used for any poles that are within clear zones. – For poles in the median – install two shorter poles on both sides of the tall launch pole to increase the width of the landing area and reduce the risk of gliders missing the pole and colliding with vehicles. Shorter poles should be approximately 10 m tall or a height of 2 m above where gliders are expected to land. The shorter poles should be touching the tall pole and

ASPECT	DESIGN CONSIDERATIONS
	secured with long galvanised bolts. If there are no trees in the median, include cowls on the median poles to prevent gliders descending. If there are trees in the median, cowls are ineffective because gliders can easily glide to adjacent trees. • Launch cross-arm: – The launch cross-arm must be at least 2 m in length, and preferably more, and point towards the opposite side of the road (i.e. in the direction of the glide). This will shorten the length of the glide required. A pair of cross-arms can be used to provide additional launch points, including to glide parallel to the road or railway. – The cross – arm should be non-treated hardwood as this is where fauna will spend most of their time. • Glide trajectory of every glider pole array must be drawn to scale to finalise pole height and spacing using the following parameters: – Glide angles in Table 9(b). – When calculating glide trajectories from glider poles, use the height and position of the end of the cross-arm, which is where gliders will typically launch from. – When calculating glide trajectories from trees, assume gliders launch from the outer canopy at approximately 75% of tree height. – The projected glide trajectory must be at least 9 m (and preferably more) above travel lanes and railway tracks (4.5 m above height of tallest vehicle at 4.5 m) and 3 m above any obstructions (e.g. noise walls). – The projected landing height on a tree or pole must be a minimum of 3 m above the ground. – Successful glides must be achievable in both directions. • Identify important access trees adjacent to the road or railway during detailed planning and design and protect these during construction
Landscape position and fencing	• The position and spacing of glider pole arrays depend on the target species. Glider pole arrays for species with a small home range may need to be every few hundred metres, while arrays for species with larger home ranges may need to be every few kilometres. • Poles must be accessible for maintenance and/or installation of cameras or other monitoring. • Glider poles should be built where native vegetation/habitat for the target species occurs (or can be replanted) on both sides of the road. • It is not possible to build effective fences for arboreal mammals and glider poles. Therefore, install in high quality habitat, along existing corridors, or movement paths and at natural pinch points.
Landscaping and vegetation	• Additional poles and/or tree planting may be required to connect the array to adjacent vegetation. Trees should be planted around the base of all glider poles to provide a larger area for gliders to land on and reduce the likelihood of them missing the landing and colliding with vehicles. • If insufficient vegetation is present, vegetation must be planted to encourage fauna to use the glider poles, in accordance with Section 16.1.

ASPECT	DESIGN CONSIDERATIONS
Furniture and enhancements to encourage use	• Include a metal predator shield at the top of the pole to provide protection from aerial predators. The shield must be a circular galvanised metal plate, approximately 900 mm diameter and at least 500 mm above the cross arm. • Include one open-ended length of 100 mm diameter UPVC pipe (or equivalent), approximately 400 mm in length, installed horizontally on the poles at about halfway up the pole and another to the underside of the cross arm to provide protection from aerial predators.
Lighting	• Where possible, avoid artificial lighting within 100 m of glider poles. • Where lighting is required to meet safety standards, refer to Section 19.5.
Maintenance	• Inspections of pole integrity and condition of predator protection is required every two years. • Foliage from trees that grow around the glider pole will facilitates access by fauna and this vegetation should be allowed to grow. • Any significant failures (those that prevent use by target species) should be rectified as soon as possible to ensure operational performance is not compromised. Ecological failure of a structure could result in loss of ecological connectivity for potentially long periods of time, which could have severe consequences for local fauna. • Inspections should be conducted by an appropriately qualified person experienced in the design, assessment, and function of FSTID (Chapter 8).
Monitoring and performance evaluation	• Develop and implement a performance evaluation plan, in accordance with Chapter 3.

Table 9(b) – Glide angles and horizontal distances for selected species of gliders

SPECIES[1]	GLIDE RATIO (ANGLE)[2]	HORIZONTAL GLIDE DISTANCE[3]	SOURCE
Squirrel glider	1.84 (29°)	29.8 m	(Goldingay and Taylor 2009)
Sugar/Krefft's glider	1.82 (28.8°)	28.8 m	(Jackson 1999)
Greater glider	1.19 (40°)	13.8 m	(Wakefield 1970) cited in (Jackson 1999)
Yellow-bellied glider	2.0 (27.3°)	32 m	(Goldingay 2014)
Mahogany glider	1.91 (28.3°)	29.71 m	(Jackson 1999)

Notes:

[1] No data for feathertail glider, but average glide length 14 m (launch and landing height not recorded) from Perth Zoo fact sheet.

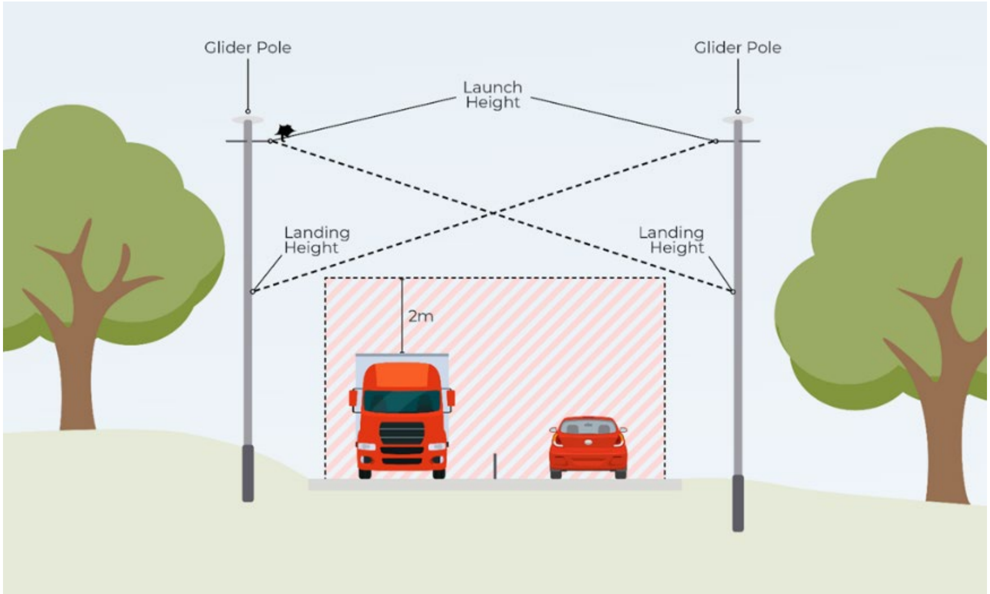
[2]. Glide ratio is horizontal distance travelled divided by the vertical drop. Glide angle is measured from the horizontal.

[3]. Glide distance assumes launch height of 16.5 m and landing height of 5.0 m, across flat ground. Launch height based on 20.0 m pole set 3.5 m into the ground with launch from cross beam at 0.5 m from top of pole. Landing height assumes a 3.0 m landing height plus a 2.0 m buffer. Detailed designs must be completed for all projects. Taller and/or more poles are required to achieve safe glides.

Figure 9(a) – Glider Pole in centre median and verge of Princes Highway, south coast of NSW

Source: © Rodney van der Ree, WSP

Figure 9(b) – Schematic to calculate glide angles and glider-pole spacing. Glides must be achievable in both directions across the road or railway and always be a minimum of two metres above the height of the tallest truck or train



10 Glider poles – under bridge

Under-bridge glider poles are standard glider poles installed under road bridges and can include timber poles and/or retained or installed tree stumps . The intention is to achieve a single row or ideally a 10-20 metres wide strip of poles and/or tall tree stumps under bridges which allows gliders to traverse the gap using multiple small glides. The use of under-bridge poles eliminates the risk of gliders colliding with vehicles while attempting to glide above the roadway.

Table 10 – Glider poles (under bridge)

ASPECT	DESIGN CONSIDERATIONS
Target species	• Likely effective for squirrel gliders, sugar gliders, Krefft's gliders, feathertail gliders, and mahogany gliders, but further research required. • Unlikely suitable for greater gliders and yellow-bellied gliders because they typically occur higher in the canopy, but further research required.
Design, dimensions and construction materials	• As for Section 9. • If retained tree stumps are part of the array, calculate glide trajectories based on a launch-height of the top of the stump. • Gliders must be able to land a minimum of 2 m above the ground. • The top of the poles or tree stumps should be approximately 1-2 m below the underside of the bridge structure. • Timber poles and retained stumps should be positioned away from bridge supports to prevent damage to the bridge structure if they collapse. • Prune the tree and reduce the weight of the canopy to minimise the risk of collapse and damage to the bridge structure. • Each retained stump should be inspected and pruned at construction by a qualified arborist with a minimum Level 3 Certificate in Arboriculture or equivalent plus demonstrated experience in inspecting and pruning trees for habitat. • Maintain as much canopy adjacent to the bridge structures where the stumps will be retained as possible to provide connection to the stumps and provide shelter to the stumps from extreme wind to increase their standing lifespan.
Landscape position and fencing	• As for Section 9.
Landscaping and vegetation	• As for Section 9.

ASPECT	DESIGN CONSIDERATIONS
Furniture and enhancements to encourage use	• Tree stumps are likely better than timber poles because they are wider and offer a larger landing surface, and provide habitat in the form of bark, hollows, and potentially canopy growth if they are retained alive. • Consider the likely standing life of the tree compared to a treated pole. Standing life of dead trees is influenced by tree species, resistance to termite damage and decay, root base, current condition, and position in the landscape (e.g. in swampy vs drier area). • Carved hollows can be installed into retained stumps if the stems are sufficiently large. • If the trees are River Red Gums (*Eucalyptus camaldulensis)*, they are resistant to decay and with the root system still intact, they should remain standing for at least 30 years, if not longer[42] • Trees that survive pruning and construction may have coppice regrowth for some years, which provides shelter and food for fauna and increases the useful standing life of the stump because the root system remains alive. However, retained stumps under bridges are unlikely to survive in the medium-term due to extensive pruning, reduced sunlight and soil moisture levels, and compaction of soil during construction, and hence ongoing inspection by arborists is unlikely to be required. • Predator shields and refuge pipes are not required on poles under bridges because the road bridge provides protection from aerial predators. Predator shields and refuge pipes are required on poles and stumps at the end of arrays that are not protected by the road bridge.
Lighting	• As for Section 9.
Maintenance	• As for Section 9. • If the stumps, branches, or coppice regrowth is within striking distance of the bridge piers, they should be inspected by a qualified arborist at least once every two years to assess health and residual risk. Coppice regrowth is poorly connected to the main stem and poses a higher incidence of failure than normal branches. A qualified arborist should advise on the required re-inspection frequency. • The structural root zone of each retained stump should not be damaged during maintenance works because these are what will support the tree stump in the long term. • Inspections should be conducted by an appropriately qualified person experienced in the design, assessment, and function of FSTID (Chapter 8).
Monitoring and performance evaluation	• Develop and implement a performance evaluation plan, in accordance with Chapter 3.

[42] Grant Harris, Ironbark Environmental, pers. comm.; Cameron Ryder, Ryder Consulting, pers. comm

11 Canopy connectivity

Canopy connectivity is an effective approach to facilitating connectivity for arboreal mammals, birds, and bats by maintaining trees and shrubs as close to the road and railway as possible, ideally allowing tree canopy from opposite sides of the transport infrastructure to remain connected . This approach minimises the size of the break in canopy, encouraging gap-sensitive fauna to fly or glide across, or by allowing non-gliding arboreal mammals to climb between canopies. While full canopy connectivity is not feasible on wide roads and electrified railways, partial canopy connectivity can significantly reduce the barrier effect for many species, including birds and bats, and should be considered.

Canopy connectivity provides habitat, but the focus for transport design and management in this context is primarily to facilitate the movement of fauna.

Canopy connectivity can also be achieved on land bridges by planting trees (Section 6).

Wherever possible, tree clearing for construction and maintenance should be kept to a minimum and undertaken strategically to ensure the tree canopy remains continuous, or gaps are small enough that species are willing and capable of crossing. For example, any gap in the canopy will affect possum movement, forcing them to come to the ground to cross. Gaps of 20-30 metres with high traffic volume will begin to limit the movement of gliders and some species of gap-sensitive birds (Chapter 9) and microbats (Chapter 11). Canopy bridges and glider poles will assist the movement of possums and gliders if canopy connectivity cannot be achieved.

The protection of individual trees or stands of trees on verges or in medians within the crossing zone for gap-sensitive species is particularly important and should be identified during project planning. Trees that must be cleared during construction and maintenance activities should be re-established as soon as possible, noting that trees may take many decades to develop a canopy analogous to the one destroyed. This time delay is critical for some arboreal species that are endangered.

Fauna exclusion fencing may be required when trees occur close to the road or railway to reduce the risk of WVC if terrestrial fauna are attracted and attempt to cross the road. Where possible, combine fauna exclusion fencing and safety barriers to protect vehicles and exclude fauna.

It is important to note that while this approach facilitates the movement of fauna, it doesn’t eliminate the risk of WVC. Therefore, this approach is more suitable when:

- Roads and non-electrified railways are narrower and/or have vegetated medians.
- Vehicle speeds are slower.
- Traffic or train volume is lower, and importantly at the time of day when the target species may attempt crossing the road.
- Visibility of oncoming vehicles is high, allowing fauna to detect oncoming vehicles and potentially time their movement accordingly.
- The target species has relatively low rates of WVC, is not of conservation concern and responds appropriately to oncoming vehicles.

The typical approach to minimise the extent of clearing is to reduce the width of the median as much as possible and keep the footprint as small as possible. However, there may be occasions when greater connectivity outcomes for gap-sensitive species can be achieved by creating a wider median and retaining trees in the median. This may result in slightly higher clearing extent, but could reduce overall gap-sizes to be crossed. Expert opinion should be sought, including an arborist assessment of the likely consequences of increased wind exposure on tree survival.

12 At-grade crossings

At-grade crossings are where fauna cross the transport infrastructure at ground-level. At-grade crossings can also refer to specific locations where fauna are encouraged or directed to cross the road or railway, sometimes with design features to decrease the risk of WVC.

At grade crossings are not recommended on new transport projects in areas with important fauna populations and/or where there is a high risk of WVC. In those situations, fauna exclusion fencing (Section 13) and wildlife crossing structures (Section 3 to Section 10) are required.

At-grade crossings may be a suitable temporary solution at locations with high rates of fauna crossing and high rates of WVC and where an infrastructure upgrade is planned to occur in 5 to 20 years.

The following considerations should be applied when at-grade crossings are being considered:

- Use fences or other structures to funnel fauna towards a preferred crossing location.
- Consider speed management at a small number of specific locations and install advanced signage to reduce WVC.
- Minimise road or railway width so fauna are attracted to cross quickly and remain in the specific crossing area.
- Undertake comprehensive monitoring, evaluation, and reporting to quantify effectiveness and implement adaptive management if required (Chapter 3).

13 Fauna exclusion fencing

Fauna exclusion fencing along transport infrastructure performs two functions:

- Reduces the rate of WVC by preventing fauna from accessing the road or railway, thereby reducing injury and mortality of fauna and increasing user safety.
- Funnelling fauna to crossing structures, thereby increasing their effectiveness.

A review of the international scientific literature showed that roadside fencing that is correctly designed, installed and maintained can reduce rates of mortality on roads by an average of approximately 50%, and up to almost 100% in some situations[43]. While fencing alone is the most effective method to reduce WVC[44], it increases the barrier effect by preventing animals from crossing the road or railway. Therefore, fencing and crossing structures are typically installed together in a co-ordinated manner. Fauna exclusion fencing without crossing structures should only be considered under specific circumstances (Section 13.1).

Fauna exclusion fencing must be designed specifically for the target species to maximise its effectiveness. Common fencing designs exist for most terrestrial species including macropods, koala, reptiles, and amphibians. General design specifications are provided in Table 13.2(a), with species- or taxa-specific details in Table 13.2(b) to Table 13.2(f). Refer also to Transport and Main Roads Standard Drawings.

Other types of structures, such as noise walls (Section 19.4), light walls (Section 19.5), and safety barriers (Section 14) can also function as fauna fences if designed appropriately.

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[43] (Rytwinski et al. 2016)
[44] (Rytwinski et al. 2016)

13.1 Fencing without crossing structures

Fencing should rarely be installed without fauna crossing structures and requires careful consideration prior to implementation. Fencing without crossing structures will act as a complete barrier to the movement of many species of fauna, effectively dividing populations into two and potentially preventing access to food, shelter, and mates. In certain situations, it may lead to localised extinction of a population.

The need for fencing without crossing structures must be assessed on a species and location-specific basis, and the negative and positive consequences identified and evaluated. There will be many situations where a fence will assist some species but have a detrimental effect on the viability of other species. Fencing without crossing structures may be appropriate when some of the following conditions apply:

- The greatest threat to the target species is mortality from WVC which will reduce the size of the local population and/or cause local extinction.
- The target species is listed under state or national legislation.
- The population of the target species in the vicinity of a road is large or occurs at high density and can persist with reduced movement.
- The target species and other species impacted by the particular fence only need to cross a road infrequently, such as for occasional dispersal.
- The WVC causes significant motorist injury and/or vehicle damage and no other options are viable.
- There are numerous opportunities in relatively close proximity to the fencing where suitable crossing structures exist, or existing drainage structures can be modified.
- Habitat occurs on one side of the road and the other side is hostile, such as industrial, residential, or high-intensity agriculture, resulting in fauna mortality due to WVC and likely fauna injury and mortality in the hostile landscape.
- The opposite side of the road already has a barrier in place for the target species, such as steep cuttings or a retaining wall.

13.2 Fence design

General fence design principles are described in Table 13.2(a) Fencing requirements for specific fauna groups are provided in Table 13.2(b) to Table 13.2(f).

Table 13.2(a) – Design considerations for fencing – overarching considerations

ASPECT	DESIGN CONSIDERATIONS
Target species	• Proven for many target species, when designed accordingly, including most terrestrial species including macropods (Table 13.2(c)), koala (Table 13(b)), reptiles, some arboreal mammals (Table 13.2(e)), and amphibians (Table 13.2(f)). • Not effective for gliders as they can glide above the fence from adjacent trees and many arboreal species can climb over. • Special designs required for ground-burrowing species.

ASPECT	DESIGN CONSIDERATIONS
Design, dimensions and construction materials	• Fauna fencing is typically installed to both prevent fauna from accessing the road (to reduce WVC) as well as funnel fauna to crossing structures. • The height, length, design, and construction materials are species- and site-specific. • Always consider unintended impacts of fencing and other structures (e.g. rub rails) to other species, such as entanglement and restriction of movement where not required. • Noise walls (Section 19.4), light walls (Section 19.5), and safety barriers (Section 14) can potentially function as fauna fencing if designed appropriately. • Choice of material is situation dependent – plastic-coated wire mesh will reduce rust and corrosion in but will melt during bushfire. • Dark coloured mesh is less visually obtrusive than galvanised mesh. • Solid and/or opaque material that fauna are unable to see through may be more effective than mesh, which some species will move along trying to pass through. • General design principles: – Barbed-wire should never be used near fauna crossing structures, particularly those for arboreal species, as gliders frequently get entangled and die[45]. Barbed wire should also be avoided near habitat for gliders, flying-foxes, wetland birds and within waterways. – Consider risk of entanglement to other species, such as kangaroos and emus, getting tangled in the top strands. – Fauna fences should typically be installed on both sides of transport infrastructure. Refer to Section 13.1 for when fencing on a single side only. – Consider placement and strength of fence in areas subject to flooding. – The base of fencing should be buried to prevent digging underneath or secured to the ground with a concrete strip. – Avoid installing fences over drainage lines as the movement of water and branches may damage the fence. Where required, consider 'flaps' that can open and let water through, and close after the water flow has ceased. A potential option is chains (with 30 mm minimum pitch and 7 mm wire dimension) installed vertically, but not attached to ground, to create a perceived barrier to minimise fauna movement through drainage lines while maintaining water flow. Further research on effective designs is required. – Design fencing for multiple species and multiple purposes (e.g. fauna exclusion, property boundary), where possible. • Where fencing is installed to funnel fauna towards crossing structures: – In general, fencing should be installed at every crossing structure. – Ensure fauna fences are attached securely to crossing structure, such as abutment walls, wing walls or pillars, thereby ensuring fauna are funnelled directly to the crossing structure and are unable to squeeze between crossing structure and fence. Permissible gap-size is species-specific. – Fauna fencing should typically include a 'return' – an angled section of fence (the last 10-20 m of fencing) to encourage fauna to turn back towards their habitat rather than move around the fence end and onto the transport infrastructure. – Where possible, fence ends should be integrated with other infrastructure, such as boundary fencing, natural barriers e.g. cliffs, cuttings, rocky areas, or other geographical features that limit movement of the target species. • Fence length – It is not possible to specify a standard minimum or maximum length of fencing that is required because it depends on various interacting factors,

[45] (van der Ree 1999)

ASPECT	DESIGN CONSIDERATIONS
	including the extent of habitat in the area, the occurrence and movement patterns of the target species, and risk of fauna vehicle collision. An experienced ecologist should be consulted. – The fence should be long enough to prevent target species from accessing the road. This typically corresponds with the occurrence of habitat and/or distribution of the target species along the road. The fence will need to extend further if the target species is willing to pass through 'non-habitat'. – Short fences either side of a crossing structure are typically less effective than long lengths of continuous fencing because fauna may access the transport infrastructure via the fence end, increasing the rate of WVC there, an effect known as the 'fence-end effect'[46]. Continuous fencing may not be feasible, especially when retrofitting fencing to existing transport infrastructure, and careful design is required to maximise the exclusion and funnelling effect and minimise the 'fence-end' effect. – For preliminary planning purposes, assume 500 m of fencing at each crossing structure and continuous fencing where it passes through large areas of habitat. This will be further refined during detailed design. • Gates and fencing breaks: – Intentional breaks in fencing are required to allow vehicles and/or pedestrians to access side roads, tracks, and driveways, especially in urban, suburban, and peri-urban settings. Such breaks are vulnerable points in fencing systems and may allow fauna to access transport infrastructure and should be avoided where possible. – Where necessary, breaks in fencing can be treated with gates, fauna grids (i.e. modified cattle grids, Section 15.1), or wrap-around fencing. – Gates are problematic if left open, poorly designed, or not maintained. All vehicle gates should be locked to minimise unauthorised use and reduce likelihood of being left open. Pedestrian gates should be turnstiles and/or self-closing. Avoid gaps between the gate and fencing and the gate and the ground. Allowable gap sizes are species-specific. – Cattle grids can be effective if the target species avoids walking on them. A small number of monitoring reports indicate they are successful for koalas[47]. Grid width and spacing of bars may need modifying for other species and further research is needed. Grids can be trip hazards cyclists, pedestrians, and fauna. – Fencing can also be extended along the intersecting road (i.e. wrap-around fencing) in the form of a long return – see notes on fence length to inform this.
Landscape position and fencing	• Fencing is required wherever the target species or its habitat occurs and where the target species can access the transport infrastructure. • The fence typically needs to be accessible on both sides to undertake inspection, maintenance, and vegetation control. • Vegetation must be managed to prevent fauna from climbing over the fence. Clearing requirements vary according to vegetation type, fence height, the target species, and their climbing ability, but are typically 1 m wide on the transport side and 3 m wide on the habitat side. • Where possible, fauna fencing should aim to maximise the area of fauna habitat behind the fence, minimise the extent of vegetation clearing, and enable maintenance and be integrated with property fencing to save costs and avoid unnecessary parallel fencing.

[46] (Huijser et al. 2016, Plante et al. 2019, Spanowicz et al. 2020)
[47] (DPIE 2020)

ASPECT	DESIGN CONSIDERATIONS
Landscaping and vegetation	• Fencing is difficult to install in areas with frequent changes in vertical geometry and earthworks may be required to eliminate gaps underneath. • Steep and high cliffs or cuttings / batters may function as barriers to movement and fencing may not be required in these situations. Heights and slopes are species-specific, but as a guide, slopes must be at least 1.5 vertical to 1 horizontal and at least 4 m tall. Further research is needed to clarify and confirm these values. • Consider drainage and water flow to prevent damage to fences during floods.
Escape mechanism	• Ensure appropriate escape mechanisms (e.g. one-way gates, escape ramps and dropdown poles, refer to Section 15) where fauna fencing is continuous for lengths that exceed half of the typical home range of the species.
Maintenance	• All fauna fencing, gates, escape mechanisms and other associated infrastructure should be inspected annually, after major floods and fires, and whenever vandalism, collisions, or other damage is reported. • Fences should be inspected for 1 km in both directions after a WVC has been detected. • Any significant failures (those that prevent use by target species) should be rectified as soon as possible to ensure operational performance is not compromised. Ecological failure of a structure could result in loss of ecological connectivity for potentially long periods of time, which could have severe consequences for local fauna. • Inspections should be conducted by a suitably qualified person experienced in the design, assessment, and function of FSTID (Chapter 8).
Monitoring and performance evaluation	• Develop and implement a performance evaluation plan, in accordance with Chapter 3.

Table 13.2(b) – Design considerations for koala fencing

ASPECT	DESIGN CONSIDERATIONS
Target species	• Effective for koalas and potentially macropods if >1.8 m tall
Design, dimensions and construction materials	• 1.2 m to 1.8 m in height. Refer Transport and Main Roads Standard Drawing SD1603 *Fencing – Koala Proof Fence and Gate* and SD1615 *Fauna Exclusion Fencing – Floppy Top Mesh Fence and Gate* for detailed design. • Use cyclone mesh fence – see Table 13.2(a) for mesh-type considerations. • Install a 600 mm wide strip of smooth, opaque sheeting (e.g. green or black high-density polyethylene or sheet metal) at the top of the fence to prevent koalas from gaining grip and climbing over. Recycled plastic sheets can be used, however will melt during fires. Ensure the top of the strip sits above the top of the cyclone mesh to prevent entanglement by birds, bats, flying-foxes, and gliders. There have been trials of placing this sheeting at 1200 mm (Gold Coast) and 1000 mm (NSW) as this reduces the visual impact of the sheeting where fencing is adjacent to public areas. • Sheet metal strips can be added to other types of fencing (e.g. controlled access / boundary fencing) or structures (e.g. noise walls). Polyethylene panels are not recommended as these pose a fire risk. • Gaps under fences and gates, and between gates must be <10 cm (size of juvenile koala head). The bottom of the fence should be attached to a concrete strip along the base. • May also be effective for possums, antechinus, and brush-tailed phascogale if the mesh is fine. • Grids may be effective, refer to Table 13.2(a) for details

ASPECT	DESIGN CONSIDERATIONS
Landscape position and fencing	• Refer to Table 13.2(a) for details.
Landscaping and vegetation	• Refer to Table 13.2(a) for details.
Escape mechanism	• Provide escape mechanisms when fencing >500 m in length. • Likely escape mechanisms include one-way gates (Section 15.3) and escape poles (see Section 15.4), but more research needed.
Maintenance	• Refer to Table 13.2(a) for details.
Monitoring and performance evaluation	• Refer to Table 13.2(a) for details.

Table 13.2(c) – Design considerations for macropod fencing

ASPECT	DESIGN CONSIDERATIONS
Target species	• Effective for kangaroos and wallabies.
Design, dimensions and construction materials	• Refer Transport and Main Roads Standard Drawing SD1603 *Fencing – Koala Proof Fence and Gate* and SD1615 *Fauna Exclusion Fencing – Floppy Top Mesh Fence and Gate* for detailed design. • Minimum of 1.8 m and ideally 2.1 m in height. • Use cyclone mesh fence, refer to Table 13.2(a) for mesh-type considerations. • Kangaroos frequently attempt to jump fences and the top 300 mm of fence must not have single wires or large open mesh that could entrap their feet.
Landscape position and fencing	• Refer to Table 13.2(a) for details.
Landscaping and vegetation	• Refer to Table 13.2(a) for details.
Escape mechanism	• Provide escape mechanisms when fencing >500 m in length. • Escape mechanisms include jumpouts (Section 15.2) and one-way gates (Section 15.3), but more research is needed to refine the design (Section 15.2).
Maintenance	• Refer to Table 13.2(a) for details.
Monitoring and performance evaluation	• Refer to Table 13.2(a) for details.

Table 13.2(d) – Design considerations for small mammal fencing

ASPECT	DESIGN CONSIDERATIONS
Target species	• Effective for small mammals. Potentially effective for other small species and non-flying birds (e.g. juvenile chicks) that are not capable of jumping, but more research required.

ASPECT	DESIGN CONSIDERATIONS
Design, dimensions and construction materials	• 0.6 m in height. • Ideally use opaque sheeting (e.g. high-density polyethylene or sheet metal) that prevents them from seeing through. Recycled plastic sheets can be used, however will melt during fires. Where drainage needs to be achieved through the fence it can have small perforations, as small as possible with a maximum perforation diameter of 10 mm or a diameter that prevents the movement of the target species. • If using a mesh fence, the mesh size depends on target species: 35 mm for adult bandicoots and smaller for juveniles – consult a specialist for mesh sizes. • There are anecdotal reports of injuries to small mammals from interactions with mesh fencing, including echidnas damaging their snout. • Can be stand-alone or affixed to another fence or structure.
Landscape position and fencing	• Refer to Table 13.2(a) for details.
Landscaping and vegetation	• Refer to Table 13.2(a) for details.
Escape mechanism	• Provide escape mechanisms when fencing >500 m in length. Escape mechanisms include jumpouts (Section 15.2) and one-way gates (Section 15.3) but more research is needed as all trials in Australia have focussed on macropods or koalas and none have focussed on small mammals.
Maintenance	• Refer to Table 13.2(a) for details.
Monitoring and performance evaluation	• Refer to Table 13.2(a) for details.

Table 13.2(e) – Design considerations for arboreal fauna fencing

ASPECT	DESIGN CONSIDERATIONS
Target species	• There are no standard designs for fencing for arboreal species, except koalas (Table 13.2(b)).
Design, dimensions and construction materials	• Likely effective designs will consist of smooth and opaque sheet metal or plastic that they are unable to climb, to a height of 1.8 m. Careful attention to detail to exclude or modify features they may use to climb (e.g. joins, posts) is required. • If mesh, it must be small enough to prevent egress by juveniles of the target species. • All fencing must be securely buried or concreted to prevent fauna from passing underneath. • There is currently no fencing that effectively excludes gliders as they can glide from adjacent trees over the fence. • Overhanging trees will be used by arboreal species to cross the fence.
Landscape position and fencing	• Refer to Table 13.2(a) for details.
Landscaping and vegetation	• Refer to Table 13.2(a) for details.

ASPECT	DESIGN CONSIDERATIONS
Escape mechanism	• Provide escape mechanisms when fencing >500 m in length • Escape mechanisms potentially include jumpouts (Section 15.2) and one-way gates (Section 15.3) for possums and escape poles for possums and gliders (Section 15.4), but more research is needed.
Maintenance	• Refer to Table 13.2(a) for details.
Monitoring and performance evaluation	• Refer to Table 13.2(a) for details.

Table 13.2(f) – Design considerations for amphibian and reptile fencing

ASPECT	DESIGN CONSIDERATIONS
Target species	• Effective for amphibians and reptiles.
Design, dimensions and construction materials	• At least 0.5 m high, have an overhanging lip (between horizontal to 45° downwards) of at least 100 mm on the habitat side of the fence, and be buried into the soil at least 100 mm. The fence should consist of a single piece of material from the top of the lip to the bottom of the buried section. • Use opaque sheeting (e.g. high-density polyethylene or sheet metal) as frogs and reptiles are more likely to move along opaque fence than mesh, which they can see through. • Fencing near waterways may be prone to floods and flood damage. Where drainage through fencing required, use opaque sheeting with perforations <10 mm diameter to prevent movement of juvenile frogs. • Stainless steel mesh has been used on Healesville-Koo Wee Rup Road duplication in Victoria and Bruce Highway Upgrade: Caloundra Road to Sunshine Motorway (CR2SM) in Queensland. • Standard sediment fencing (i.e. geotextile / silt fence) is only recommended for temporary structures due to rate of degradation of material and high maintenance needs. • Frogs and reptiles will use adjacent vegetation to climb up and over the fence. Vegetation that may overhang the fence should not be planted or allowed to grow (see maintenance Section in this table). Taller fencing (e.g. 1000 mm) will reduce the frequency of mowing or other vegetation management and thus may be preferable than shorter fencing. • Can be stand-alone or affixed to another fence.
Landscape position and fencing	• Refer to Table 13.2(a) for details.
Landscaping and vegetation	• Refer to Table 13.2(a) for details.
Escape mechanism	• Effective escape mechanisms for amphibians and reptiles are likely required, but have not been designed and tested.
Maintenance	• Refer to Table 13.2(a) for details. • Slashing may be required once every month or two during the growing season to prevent understorey from overtopping the fence and enabling frogs and reptiles to cross over.
Monitoring and performance evaluation	• Refer to Table 13.2(a) for details.

14 Safety Barriers

Some types of safety barriers (e.g. rub rails installed on w-beam safety barriers and concrete jersey barriers) may be physical barriers to the movement of some fauna, especially small terrestrial species. If installed on both sides of the transport infrastructure, they may be as effective as fauna exclusion fencing (Section 13). Where the safety barrier effectively prevents movement of the target species, the safety barrier is the fauna exclusion fencing and additional fencing is not required.

The size of the deflection zone behind different types of safety barriers varies according to the type of barrier. Therefore, safety barriers which require smaller deflection zones should be considered in areas with high value vegetation to reduce clearing extents.

Some species may be physically capable of crossing more permeable barriers (e.g. wire rope) in the absence of traffic but are hindered when vehicles approach because they become stressed and react unexpectedly. Further research on the impact of all safety barriers on the movement and behavioural response of fauna is urgently needed.

Safety barriers installed only in the median or one side of the transport infrastructure can trap fauna that would ordinarily be able to make it across, thereby increasing rates of WVC.

Use of safety barriers that trap or hinder movement should be avoided in areas with high fauna populations, unless necessary for human or vehicle safety reasons. If these barriers must be installed, the following guidance will reduce negative impacts on fauna:

- Install on both sides of the road to prevent fauna from accessing the road from either side. Crossing structures should also be installed if fauna movement is important.
- Rub rails and concrete jersey barriers that are not intended to affect fauna should not exceed 200 m in length without a break or escape mechanism installed.
- If safety barriers are trapping fauna on the transport infrastructure and increasing WVC, consider installing fauna exclusion fencing on the perimeter to prevent fauna accessing the road or railway.

Figure 14 – Safety barrier topped with perspex barrier which functions as fauna exclusion fencing

Source: © State of Queensland

15 Escape Mechanisms

Fauna can breach fencing, and escape mechanisms are required to allow them to leave the fenced transport corridor. Escape mechanisms are one-way structures that allow fauna to leave the fenced corridor, but not enter it. Escape mechanisms without moving parts (e.g. jump outs, escape ramps, or escape poles) are preferred over those with moving parts (e.g. one-way gates) because they require less maintenance. One-way gates are currently being trialled for koalas (Section 15.3).

Escape mechanisms are required along transport corridors with long lengths of fauna fencing. They are not required for short lengths where fauna can quickly or easily move to the ends of fencing to leave the transport corridor. The spacing of escape mechanisms is dependent on:

- The movement capability, including speed and distance travelled, of the target species.
- The behaviour of the target species when trapped in a fenced corridor and how quickly it is likely to find the escape mechanisms.
- The consequences of WVC for the target species (e.g. is it a threatened species?).
- Risk of injury and mortality to users from WVC (e.g. collision with large kangaroo), where escape mechanisms could be installed when fencing exceeds 250-500 m in length to reduce the time they spend trapped on the road.

The design objective is to enable fauna to quickly detect and use an escape mechanism without requiring them to search extensively or to cross the road or railway.

Escape mechanisms vary in effectiveness, and some allow movement of animals into the road reserve (see Sections 15.2 to 15.4). Therefore, there is a trade-off between allowing animals to quickly escape from the fenced transport reservation and minimise opportunities for them to enter the reservation using the escape mechanisms in reverse. As a guide, the spacing of escape mechanisms should be approximately half a home range length of the target species, the distance typically travelled in one day, or 500 m, whichever is shorter. Smaller spacing between escape mechanisms (e.g. koala poles at ~100 m intervals) may be appropriate for species at risk of extinction. Escape mechanisms that do not allow any animals to access the transport could be installed more frequently.

Escape mechanisms, such as rope ladders draped over concrete jersey barriers, may assist in helping koalas to traverse these barriers, however there are no published studies of their effectiveness.

15.1 Dealing with gaps in fencing

Gaps in fencing are required for access roads and property access across the transport corridor. Ideally, these will include gates or grids to prevent fauna from accessing the fenced road or railway (see below). If grids and gates are not feasible, consideration should be given to include a break in the fence on the opposite side of the transport infrastructure. This will enable fauna that do enter the road or railway to exit it on the other side and reduce the likelihood of them getting trapped between fencing. There is further discussion on At-grade crossings in Section 12.

However, WVC will likely increase at these locations and expert input from an ecologist is required to weigh up the pros and cons of this approach. Road markings and/or signage to warn motorists may be considered if the risk of WVC is high. However, signage and road markings are not very effective (Section 19.7), especially on roads with high speeds and high traffic volume. Over-saturation of signs and road markings will also decrease the already marginal benefit of this mitigation approach.

There is further discussion on koala grids in Chapter 13.

15.2 Jump-outs and escape ramps

Jump-outs and escape ramps are designed to allow fauna to exit the road or railway but not enter it. They function similarly but are designed slightly differently.

Escape ramps are used where the transport infrastructure is at grade and ramps on the infrastructure-side of the fence allows fauna to walk up to the height of the fence and then jump down to escape the fenced corridor (Figure 15.2(a), Figure 15.2(b)).

Jump-outs are installed where the road is on fill and fauna jump down a retaining wall, the wing-walls of culverts, or potentially bridge abutments (Figure 15.2(c), Figure 15.2(d)).

The height of the vertical drop of jump-outs and escape ramps is critical to prevent fauna from accessing the fenced corridor, and there are currently no standard designs available yet in Australia. However, early trials of ramps that were 60-80 centimetres high on the Pacific Highway in north-east New South Wales[48] found that swamp wallabies and bandicoots used the ramps extensively to access the fenced highway corridor. Therefore, they recommend that the height of the vertical drop should be 1.2 -1.4 metres to prevent use in the reverse direction by bandicoots and wallabies[49]. The height for koala escape ramps and jumpouts should be 1.2-1.4 metres and take into account designs of koala fencing (e.g. 600 mm panels) to prevent climbing. Other innovative designs could include horizontal poles above the ramp to discourage animals from jumping up. Further research is urgently required.

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[48] (Goldingay et al. 2018c)
[49] Brendan Taylor, pers. comm.

Figure 15.2(a) – Escape ramp on the Woolgoolga to Ballina section of the Pacific Highway

Source: ©Rodney van der Ree, WSP

Figure 15.2(b) – Escape ramp on the Pacific Highway

Source: © Rodney van der Ree, WSP

Figure 15.2(c) – Jump down on the wing-wall of a culvert on Beaudesert to Boonah Road

Source: © State of Queensland

15.3 One-way gate

One-way gates allow fauna to exit the road or railway but not enter it. One-way gates have rarely been recommended because they have jammed open or closed in installations overseas and require additional maintenance to ensure they operate effectively. One-way gates were trialled on captive koalas for the Moreton Bay Rail Project[50] but were not installed on the project. One-way gates have been installed on the Toowoomba Second Range Crossing, but monitoring is yet to be published. The following design guidance should be used if being considered:

- Be extensively trialled on captive animals before installation as well as extensively tested and evaluated in the wild after installation.
- Be specifically designed for the target species.
- They are more likely to be effective if the fence is opaque and the habitat can be seen through the one-way gate, encouraging fauna to investigate and attempt to 'push through'.
- Include fail-safe mechanisms to ensure fauna are unable to access the fenced transport corridor in the reverse direction (i.e. prevent door being jammed open).

[50] (Hanger et al. 2017)

- Limit the risk of injury to fauna, such as doors jamming on animals.
- Consider the risk of back-young being separated from parents or animals that move in groups becoming separated from each other when some individuals pass through, but others don't.

Figure 15.3 – Trial of rake gate for koala fencing

Source: © Endeavour Veterinary Ecology

15.4 Escape poles

A "n"-shaped pole structure installed over fences to enable trapped Koalas and other arboreal fauna to climb up and over the fence (Chapter 13). The post on the habitat side of the fence can either include sheet metal wrapping to prevent animals from climbing up, or it can terminate 1.5 metres above the ground, and in both designs, fauna must jump the last 1.5 metres to the ground to exit the fenced transport corridor. While deployed extensively in Queensland, monitoring has only been published on one project to date[51] (Chapter 13) and is currently underway on the Caloundra to Sunshine Motorway Upgrade of the Bruce Highway[52]. The lack of evidence for effectiveness is partially a result of lack of monitoring effort, and further research is required to improve the design.

16 Biodiversity Enhancement

Biodiversity enhancement includes the establishment and restoration of native vegetation and specific habitat elements (e.g. wetland, hollows, shelter) to specifically support fauna populations and FSTID.

Biodiversity enhancement must be specific to the target species. Seek advice from an ecologist on features that are appropriate to the individual species.

[51] (Hanger et al. 2017)
[52] WSP unpublished data

16.1 Revegetation

Revegetation is the re-establishment of native vegetation in areas where it has been removed or disturbed. Revegetation can create habitat for native plants and fauna, assist fauna movement, and reduce soil erosion.

Revegetation must be done in accordance with minimum standards / best practice for revegetation and supplementary planting in Queensland. Use indigenous stock wherever possible.

The plant species used in revegetation should be appropriate to the regional ecosystem at the site and consideration should also be given to the local environmental and site conditions, ease of propagation and likely availability from nurseries. Care must be taken to ensure species used in revegetation are not locally classified as environmental weeds. In addition, topsoil and seed mixes used in revegetation should be free of weed seed.

16.2 Strategic revegetation for crossing structures

Vegetation should be planted at the entrances of crossing structures to encourage fauna to use the structures. Vegetation plantings should:

- Follow the locally indigenous regional ecosystem and use indigenous stock wherever possible.
- Match the adjacent vegetation (species and compositional structure) and provide a continuation of the natural landscape unless there is a species-specific requirement to rehabilitate habitat (e.g. more trees to provide habitat for arboreal mammals vs. less trees to provide basking opportunities for threatened reptiles).
- Be shaped to funnel fauna towards the underpass.
- Consist of the preferred habitat type for the target species and preferred habitat features, such as rocks, logs, wetlands, etc.
- Be sufficiently open to maintain sightlines through the underpass.

16.3 Vegetation and habitat management

Vegetation and habitat management includes the protection, enhancement, restoration and maintenance of vegetation and habitats adjacent to transport infrastructure and includes:

- Complete restoration of habitats or ecosystems in previously cleared areas.
- The addition of specific habitat elements (e.g. litter, logs, shrubs, grass, water) or niches to increase fauna population size, support more fauna species, or to improve fauna movement along or across transport infrastructure.
- Verge management, such as mowing and slashing verges, tree pruning, or periodic fuel reduction burning.
- The maintenance regime of vegetation and habitat along transport infrastructure must balance the human safety considerations and impacts to fauna (Chapter 8). Specific considerations include:
- Ensuring threatened fauna species are not impacted by the type, frequency, time of year or severity of maintenance.
- Not using slashing techniques that kill or remove invertebrates (Chapter 20)

- Ensure the maintenance does not constitute 'clearing'. If it does involve clearing, ensure the procedures outlined in Chapter 7 are followed.
- Distances to where revegetation can occur within the road reserve, treeless vs tree plantings (driver line of sight) etc.
- Avoiding the use of plant species or habitat features that may attract fauna to transport verges, potentially increasing rates of WVC.
- Incorporating knowledge of the road-effect-zone (REZ) (Chapter 3) into vegetation management plans. For example, providing habitat specifically for a threatened species of fauna immediately next to a major road may not benefit the species if it just increases rates of WVC or if the species avoids the area due to traffic noise and light.

16.4 Carcass clean-up

Secondary collisions occur when predators and scavengers feed on WVC carcasses on roads, railways, and adjacent verges (Chapter 4). High rates of secondary collisions can occur at certain times of year and can be a major cause of fauna mortality.

The prompt collection of fauna carcasses from transport infrastructure is a simple and effective approach to reduce the rate and severity of secondary WVC. In addition, the removal of large carcasses from roads also reduces the risk of secondary collisions with more vehicles, improving road safety outcomes.

All collected carcasses should be identified to species where possible and the location of collection recorded with a GPS. The systematic use of an on-line reporting system will ensure that WVC hotspots can be identified and adaptively managed.

16.5 Risk of predation

There is a misconception that crossing structures are prey-traps for fauna because predators learn to preferentially hunt at those locations. Despite this assertion, there is no evidence that predators systematically use crossing structures in this way[53]. In addition, numerous studies, including some on canopy bridges over the Hume Freeway in Victoria and NSW, found the same individuals using the bridges over multiple years, demonstrating successful long-term use without substantial predation by owls[54].

Nevertheless, predation and attempted predation can occur at crossing structures because they can be used by both predators and prey, potentially at the same time [55]As such, fauna crossing structures should contain furniture (Section 16.6) and be coupled with a monitoring, evaluation, and adaptive management program (Chapter 3) to evaluate if predation is occurring and a significant problem.

16.6 Fauna furniture for crossing structures

The provision of 'fauna furniture' within and at the entrance to crossing structures is considered important to maximise the rate of use by fauna and minimise the risk of predation, particularly for threatened species, species vulnerable to predation, and those that avoid open areas.

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[53] (Little et al. 2002, Mata et al. 2015, Soanes et al. 2017, Goldingay et al. 2022)
[54] (Soanes et al. 2015)
[55] (Goldingay et al. 2022)

Most fauna furniture is relatively low-cost, and examples of furniture and other habitat enhancements to reduce the likelihood of predation, include refuge pipes, rocks, logs, branch piles, and the use of above-ground ledges, shelves, and rails. Fauna furniture can include artificial shelters and natural features that are specific to the target species. Furniture can be installed on the ground, attached to walls, or built into the structure itself. These are all described in relevant species profiles (Chapters 9 to 20) and the descriptions of the various types of crossing structures (Sections 3 to 10) and Sections 16.7 to 16.9.

The inclusion of fauna furniture in fauna crossing structures that are also used for drainage must be identified in early reference designs to ensure that it is accounted for in flood modelling. The size of bridges and culverts may need to be increased to consider any hydraulic restrictions imposed by the furniture.

Fauna furniture should be secured in place (e.g. concreted into the floor of culverts or bolted into culvert wall and bridge piers) to ensure it is not washed away during flood events.

Further research and experimental trials are required to quantify the effectiveness and enhance the designs of different types of fauna furniture.

16.7 Artificial shelters and roosts

Artificial shelters and roosts provide habitat and are intended to provide medium to long-term habitat functions for different target species. Artificial roosts and shelters can be made from degradable structures (e.g. wood) which are expected to break down over time and will eventually be replaced by native vegetation plantings and natural habitat features once established. If future access within the crossing structure is likely to be restricted, with limited ability to replace or maintain fauna furniture, use only non-biodegradable furniture within the crossing structure. Non-biodegradable structures are expected to last many years and can be placed within structures (e.g. a culvert floor) or built into the structure itself (e.g. pre-cast bat roosts).

The following are design considerations for artificial shelters and roosts:

- Wooden artificial shelters should be constructed using hardwood or marine ply for greater longevity.
- Non-biodegradable shelters should be constructed from materials such as concrete or recycled plastic. Care must be taken to ensure materials will not break down and introduce pollutants into waterways.
- Non-biodegradable shelters include concrete, terracotta, or steel pipe (approx. 15 cm diameter, 0.4 m to 1 m in length) stacked to mimic a log pile, with numerous options for small fauna to enter and exit.
- Microbats use bridges and culverts as roosts and these structures can be specifically designed to accommodate roosting by these species, such as culverts and bridge beams with pre-cast roosting opportunities. Refer to Chapter 11 for details.

16.8 Elevated logs and refuge poles

With sufficient clearance from the structure ceiling, crossing structures can include elevated logs and refuge poles to provide alternative pathways and allow fauna to avoid predators. Monitoring of two culverts under the Pacific Highway in New South Wales found that the brown antechinus (*Antechinus stuartii*), a semi-arboreal mammal, was detected more often on timber rails than on the ground[56]. Other native species, such as possums were infrequently detected, and koalas were not detected using the rails in that study.

Elevated logs and refuge poles should always be included in culverts, bridge underpasses and vegetated land bridges because they are relatively inexpensive and may protect a koala or other species from predation, as well as potentially increase rates of movement.

The following are design considerations for elevated logs and refuge poles:

- Elevated horizontal logs for arboreal mammals or log rails should be at least 300-500 mm in diameter, 1.5 m above the ground with a minimum 0.5 m clearance from the ceiling (0.75 m from the ceiling if for koalas). They should connect with trees at the entrances, and access ramps to logs should be no steeper than 1:5. Flat planks are probably better than round logs but there is little evidence to support this.
- Refuge poles should have resting platforms to provide koalas refuge from predators.
- Refuge poles inside a crossing structure should be at least 2 m tall, extend to the ceiling of the culvert, and include a 'v' shaped resting point for koalas to sit on that is at least 1.5 m from the ground and 0.5 m from the ceiling.
- Refuge poles outside a crossing structure should be approximately 4 m tall and include a 'v' shaped resting point that is at least 2.5 m from the ground for koalas to sit on escape predators at ground level.
- Horizontal logs for small mammals should be ~0.5 m above the ground with a minimum of 0.75 m clearance from the ceiling. Access ramps can be logs or soil, and should be no steeper than 1 vertical:5 horizontal. Steeper ramps may be acceptable in situations where longer ramps require habitat clearing.

[56] (Goldingay et al. 2018a)

Figure 16.8(a) – Terrestrial fauna culvert under construction, with log rails at two heights and a shelf in case of flooding

The upper log rail should be lower from the ceiling and the ends of the log rails and shelf need to be attached to adjacent vegetation and/or ground level to allow animals to access.

Source: © Rodney van der Ree, WSP

Figure 16.8(b) – Terrestrial fauna culvert with refuge poles and log rail, Eton Range (Peak Downs Highway), Queensland

Source: © State of Queensland

16.9 Habitat creation in a waterway

Significantly modified waterways can become barriers to fish movement through straightening, de-snagging, excavating and other changes that result in modified water temperatures, depth, flow rates, lack of shading, and removal of instream structures. Habitat for fish and other aquatic species should be introduced whenever waterways are significantly modified, and channels should be designed to promote habitat and ecosystem functionality. Each situation is unique, and experts should be consulted, and the follow principles applied:

- Enhance the natural characteristics whenever possible.
- Re-establish or enhance waterway based on pre-existing conditions including habitat, alignment, size, and slope.
- Include instream structures, riffles, pools, and meanders where feasible.
- Ensure scour protection requirements do not hinder movement of riparian species.
- Re-establish or enhance riparian and instream vegetation as much as possible.
- Ensure water quality is maintained or enhanced to support overall waterway health and functioning.

Habitat can also be added to waterways that have been modified historically to improve waterway health and function across the landscape. Refer to Chapter 5, Section 7 Case Study - *Burleigh to Palm Beach Fauna Sensitive Transport Infrastructure Delivery* for an example of habitat creation in a waterway.

16.10 Frog ponds

The inclusion of wetlands and frog ponds associated with crossing structures encourages and facilitates the use of underpasses by frogs as well as increasing the local frog population. For many frog species (and potentially other aquatic taxa such as freshwater turtles), wetlands associated with crossing structures are likely to play an important role in facilitating use of the underpass, as was demonstrated for the growling grass frog in Victoria[57].

Where aquatic (i.e. wetland-associated) amphibians are the target group for a crossing structure, frog ponds should be constructed at both ends of a culvert system wherever feasible. Frog ponds must be designed specifically to the target amphibian species. An experienced aquatic ecologist must be consulted to confirm the best practice design standards for the target species.

Frog ponds at culvert entrances are primarily designed to attract frogs to the culvert and facilitate movement. Any breeding that does occur is a bonus.

A supply of suitable water (e.g. treated stormwater, directed overland flows from vegetated areas) must be identified as part of the design. Water supply options must include fish exclusion measures, to prevent the introduction of predatory exotic fish (e.g. mosquito fish).

Dedicated frog ponds should not function as stormwater retention or treatment wetlands due to the risk of pollution from the transport infrastructure and damage that may be caused due periodic sediment removal maintenance activities. Similarly, stormwater retention ponds and other water treatment facilities may provide some habitat value for amphibians however their performance may be compromised by:

- The design of the wetland may not be optimal or suitable for frogs.
- Pollution entering the waterway from the road or railway may injure or kill frogs.
- Maintenance and ongoing management requirements to clean the wetland through dredging or vegetation removal to maintain its primary function for water treatment may injure or kill resident frogs and reduce habitat quality.

Therefore, wetlands that are specifically required to perform important ecological functions and provide habitat for endangered species should be designed and managed specifically to achieve that objective.

[57] (Koehler and Gilmore 2014)

16.11 Restoring Shellfish Ecosystems

Shellfish ecosystems provide a range of ecosystem services such as food provision, habitat for fish and marine invertebrates including octopuses and sea squirts, water filtration, fish production and shoreline protection. These shellfish reefs are one of Australia’s most threatened marine habitats. Globally, vast coastal waters shellfish ecosystems have been decimated with more than 85% lost or severely degraded globally through unsustainable harvesting, water pollution and reduced water quality, disease, and destructive practices such as dredging for lime production[58].

Shellfish reef restoration is likely to yield greater ecosystem benefits[59] such as increased fish stocks, enhanced marine biodiversity and reduced streambank erosion. In 2023, the M1 Pacific Motorway Upgrade Project integrated three different types of structures containing recycled oyster shells (robust oyster baskets ROBs, quilted oyster doonas QODs and biodegradable mesh bags[60] within scour protection upstream and downstream of the Saltwater Creek culvert near Currumbin Creek. The site will be monitored for three years by marine scientists to assess improvements to streambank stabilisation, marine biodiversity and to gain knowledge of oyster reef restoration.

Figure 6.11(a) – Installing biodegradable mesh bags for streambank erosion protection

Source: © Seymour Whyte Constructions

58 (Gillies, 2018).
59 (Richardson, 2022
60 (OzFish, 2023)

Figure 6.11(b) – Installed robust oyster baskets and quilted oyster doonas to enhance marine biodiversity

Sources: © State of Queensland

17 Replacement tree hollows

More than 300 species of native vertebrate fauna in Australia rely on tree hollows for survival[61]. Because of their importance, trees with existing hollows and trees large enough to form hollows should be avoided and protected wherever possible on transport projects. Where they must be removed, alternative or replacement hollows should be provided to ensure there is no net loss in this important resource.

Replacement hollows can be constructed or installed using a range of techniques, including:

- Hollows carved into standing trees (Section 17.1)
- Salvaged log hollows (Section 17.2)
- Traditional nest boxes, and (Section 17.3)
- A range of new or novel types of hollows (Section 17.4).

An important consideration when preparing and implementing a replacement hollow program is the number, dimension, type, and location of hollows. The following should be considered if the program is for a specific target species:

- Ensure the hollows are the appropriate size, shape, and location in the tree.
- The number and spacing must reflect the ecology of the species. Some species need multiple hollows across their home range, others a small number centrally located.
- The total number of hollows installed must match that which has been removed or reflect the number required by the target species.

[61] (Gibbons and Lindenmayer 2002)

- If the replacement hollow program is a general program for all hollow-dependent species in the construction area, the following considerations apply:
- Install 70% of hollows prior to tree clearing, and the remainder after clearing, ensuring the remainder is adjusted once the total number of hollows being removed is known.
- It should include a wide diversity of hollow types and sizes to reflect the needs of hollow-dependent wildlife in the area.
- At a minimum, the number and diversity of hollows being installed should reflect those which are being removed. However, ideally, the number and diversity of hollows being installed should reflect the needs of the hollow-dependent species in the area and/or the number and diversity of hollows that would typically occur in an undisturbed forest. This is to give fauna the maximum chance of thriving after construction.

An experienced ecologist should be consulted to provide advice on the hollow-replacement program.

17.1 Carved hollows

Carved hollows are excavated into dead or living trees using chainsaws or other tools and mimic the thermal properties of natural hollows[62]. Carved hollows can also be installed into felled trees which can be left on the ground or re-erected as a dead tree. There is an increasing body of evidence that they provide suitable hollows for wildlife with minimal maintenance requirements[63].

Importantly, carved hollows will always be present in the tree, even if the size of the entrance or internal cavity changes over time. In some respects, the creation of a carved hollow is simply an acceleration of natural wound and decay processes in a tree, thus bypassing some decades of time for them to form naturally.

Carved hollows (Figure 17.1) are installed into relatively large host trees, with the minimum trunk diameter dependent on the size, shape, and health of the tree and the size of the hollow to be installed. As a rough guide, the minimum diameter at 1.3 metres above the ground is approximately 60 centimetres for a small hollow. Preliminary studies indicate that carved hollows are unlikely to affect tree health or kill the host tree when one or two hollows are installed in a tree and hollow size does not exceed the capacity of the limb to support the hollow[64]. Further long-term studies are required to clarify the number, size and type of hollow that can be installed without affecting the survival of the tree.

There are numerous approaches to installing carved hollows and experts should be consulted to determine the appropriate method according to the number, type and size of the hollow for the target species. Carved hollows should only be created by suitably qualified arborists (level 5 or above) to ensure the continued health of the host tree and that they are not installed in areas where there is a risk to life or property if it fails.

[62] (Griffiths et al. 2018)
[63] (Griffiths et al. 2018, Griffiths et al. 2020)
[64] Rodney van der Ree, unpub. data

Figure 17.1 – Carved hollows entrance hole (left) and inside with face plate removed (right)

Source: © State of Queensland

17.2 Salvaged log hollows

Salvaged log hollows are hollows that exist naturally in fallen or felled timber and are salvaged for use as replacement hollows. The salvaged log hollows are prepared by capping the ends of the log, installing an entrance hole (if required), and then attaching the log in a standing host tree. Salvage of natural log hollows should form part of a project's tree removal strategy, so that natural logs from the project area can be reused as log hollows on the same project. The technique used to attach the salvaged log hollow must allow the tree to grow without crushing the log hollow.

Salvaged log hollows have some disadvantages over carved hollows and nest boxes:

- They can be very heavy and difficult to lift safely into the tree.
- Hollows in living stems can crack and split as they dry.
- Hollow limbs are often damaged during clearing and require careful transport and storage before re-use.
- Hollow sizes and shapes are limited to those removed from the site, which may not satisfy the replacement program.

17.3 Nest boxes

Nest boxes are square or rectangular boxes made from plywood or timber and have been used as replacement hollows for many decades[65]. However, recent research has identified issues related to their thermal capacity, longevity, use by feral species and maintenance requirements[66], which has triggered the experimentation with alternative types of hollows.

Despite these limitations, nest boxes can still play a role as replacement hollows, especially when:

- The target species is known to readily use nest boxes.
- Temporary replacement hollows are required.
- The standing trees are too small to support carved hollows.
- A monitoring program requires frequently handling of fauna, which is achieved by opening the lid.

Where nest boxes are used, they should be:

- Well-constructed and installed to enhance longevity.
- Made from thick (~20 mm) hardwood or marine ply to insulate against temperature extremes.
- Painted to both protect the timber and painted a white colour to improve surface reflectance and minimise overheating in summer[67].

17.4 New hollow types

There is currently extensive research and trialling of new types of artificial hollows, including construction with recycled plastics, 3D printing, plastic pipes, and types of concrete, as well as variations to traditional nest boxes. The efficacy of different materials, thermal efficiency, and longevity of new designs and materials should be tested using rigorous research and monitoring (Chapter 3) and implemented if they prove successful.

18 Re-use of timber and other habitat elements

Most transportation projects result in the removal of native vegetation and habitat elements, such as fallen logs and rock. The highest priority for all Transport and Main Roads projects is to avoid clearing of vegetation and habitat wherever possible (Section 5.4.1). When clearing is unavoidable, all habitat elements should be re-used to their highest ecological value. It is not possible to specify the highest value use of all materials for all projects and ecological expertise should be sought. In addition, the local community, including first nations groups, should be engaged to assist in identifying and implementing the highest value re-use program.

18.1 Aims and principles to determine highest ecological value

The primary aim of highest ecological value re-use programs is to improve biodiversity outcomes. These outcomes will ideally be at the project site; however they can also occur off site if opportunities exist elsewhere.

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[65] (e.g. Menkhorst 1984)
[66] (Mckenney and Lindenmayer 1994, Lindenmayer et al. 2015, Griffiths et al. 2017b, Lindenmayer et al. 2017, Griffiths et al. 2018)
[67] (Griffiths et al. 2017a)

The principles to determine highest value re-use include:

- Re-use should be as close to the impact site as possible.
- Re-use should prioritise actions that enhance conservation outcomes for threatened species, and ideally those impacted by the project.
- Re-use should address deficient values in the local ecological community.
- Re-use should prioritise long-term outcomes rather than short term use.
- High quality timber should be made available for milling and high-value products that benefit the broader community, such as street furniture, architectural features, or artwork.

18.2 Engaging the community to identify best-value use of timber

Local communities should be engaged to identify high value uses that are locally relevant for social purposes, such as:

- Re-standing Aboriginal scar trees in appropriate locations and provision of wood for other traditional uses to celebrate and support indigenous culture.
- Providing milled timber to local community groups and other social groups for a wide variety of uses. Use should be determined prior to felling and milling to ensure the material is in a format suitable for the intended use.
- Use of commercial-quality timber is permitted under Transport and Main Roads contracts and should be made available for high-value uses.
- In general, re-use of high-quality timber for firewood and mulch are low-value uses.

18.3 Terrestrial habitat enhancement

Felled timber and other habitat components can be used in a wide variety of ways to enhance terrestrial habitats, including:

- Placing logs on the ground amongst revegetation or existing woodland to provide shelter to fauna, invertebrates, and fungi. Aim to enhance habitat quality in areas with low habitat value. Ensure the timber is protected from firewood collectors.
- Re-standing hollow bearing trees as habitat (Figure 6.11(a)) or glider poles (Refer to Section 10).
- Use of hollow logs as replacement hollows (Section 17.2).
- Mulch leaves and fine branches for revegetation areas.
- Collect and store topsoil for use in landscaping according to best practice techniques.
- Collect seed from vegetation prior to clearing, ensuring the timing and method of seed collection is appropriate to the species.
- Place bush rock in revegetation areas or existing vegetation to provide shelter to fauna.

Figure 18.3 – A hollow-bearing tree removed and 're-stood'; second hollow-bearing tree placed on the ground as habitat. Ravenswood Bypass, Calder Freeway near Bendigo, central Victoria

Source: © Rodney van der Ree, WSP

18.4 Aquatic habitat enhancement

Timber felled as part of transport projects is often large with complex shapes that can be reused to rehabilitate waterways, providing fish habitat. Refer to Section 6.16.9 and Chapter 19 for more details.

19 Other mitigation measures

19.1 Odour and chemical repellents

Odour and chemical repellents, such as predator scents, have been trialled overseas for reducing WVC, but have shown limited success[68]. The use of odour and chemical repellents is an appealing mitigation strategy because it may be relatively cheap, however, effective application is difficult because:

- The scent must trigger fauna to leave the transport corridor.
- The sensitivity of the same species may vary regionally, as well as amongst individuals.
- Fauna may habituate to the scent, causing it to become less effective over time.
- The effects on non-target species, including people, is unknown.
- There are logistical challenges to deployment, including frequent re-application and difficulty in applying over large distances.

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[68] (Kušta et al. 2015)

19.2 Acoustic and visual deterrents

Acoustic and visual deterrents use sounds, flashing lights, reflectors, and/or natural fauna warning signals to scare fauna from the road or rail corridor as vehicles approach[69]. These deterrents theoretically provide additional time for fauna to react to an approaching vehicle or train and reduce the probability of WVC[70]. Acoustic and visual deterrents are most likely beneficial where vehicles are obscured by vegetation or topography, or their approach is masked by other competing noises[71]. A recent trial on railways in Canada developed a system which detected passing trains with magnetic or vibration sensors and relayed the information to track-side warning systems that would alert fauna[72]. Further tests of this system concluded that animals left the track early, likely resulting in reduced rates of WVC[73]. These systems are also potentially useful on roads where continuous fencing is not feasible, such as roads with lots of driveways or other access points.

Acoustic and visual deterrents are appealing because they are relatively low cost and simple to install, and because they only operate when vehicles approach, they do not form a permanent continuous barrier. The most common visual and acoustic deterrents in Australia are roadside reflectors and virtual fencing. Unfortunately, there are few scientific trials of such systems in Australia and those that have been conducted report variable results, with only one result indicating substantial success[74]. Importantly, many of these studies have also been criticised for their lack of scientific rigour, casting further doubt on their effectiveness[75].

The inherent limitations with acoustic and visual deterrent systems include[76]:

- 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 or trains).
- 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 study and understanding of the most effective visual and acoustic stimuli for different species of Australian fauna. Most systems available in Australia were developed for European species, such as ungulates.

More research is urgently needed to explore the effects of different variables such as flashing versus steady lights, light frequency, and light brightness, especially on the night vision of nocturnal fauna[77].

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[69] (D'Angelo and van der Ree 2015)
[70] (Backs et al. 2020)
[71] (Backs et al. 2017)
[72] (Backs et al. 2017)
[73] (Backs et al. 2020)
[74] (Fox et al. 2018, Englefield et al. 2019, Stannard et al. 2021)
[75] (Coulson and Bender 2019, Coulson and Bender 2022)
[76] (D'Angelo and van der Ree 2015)
[77] (Backs et al. 2017)

Transport and Main Roads does not support the implementation of acoustic deterrents unless they are part of a scientifically rigorous and well-designed experimental trial conducted by a research agency, such as a university, in collaboration with road ecology experts. The use of increased noise or light as a mitigation needs to be balanced with the potential impact on sensitive species (Chapter 4).

19.3 Flight diverters

'Flight diverters' are potentially effective strategies to force birds and bats to fly above vehicles, and if solid structures they can also double as noise and/or light walls. Poles and flags have been trialled and some studies indicate they are effective at raising the flight height of certain species. Both solid walls and rows of poles may be effective adjacent to waterbodies and coastal areas where birds may fly low on take-off or landing[78]. Additional advantages of pole barriers include their relatively cheap price and ability to be retro-fitted to existing roadways, particularly where standard fences are more difficult to install and maintain, such as in areas prone to flooding, with high wind-loads, or in steep terrain[79].

Nets may also be effective in preventing birds and bats from flying across transport corridors at low height, however they are very likely to also result in collisions and entanglements, especially at night.

There are no standard designs or specifications for flight diverters as none have been trialled in Australia and only few have been trialled internationally.

19.4 Mitigating traffic noise

Noise mitigation may be required where transport infrastructure passes through habitat that supports fauna that are sensitive to noise (Chapter 4), typically those that:

- Rely on acoustic signals to communicate, particularly frogs (Chapter 18) and birds (Chapter 9).
- Rely on hearing to detect prey or predators.
- Use sound to navigate, such as microbats (Chapter 11).

Noise mitigation is required along roads and railways through habitat to minimise the severity and extent of the REZ caused by noise. Noise mitigation is also required on the edges of land bridges and on the approach to crossing structures.

The impacts of traffic noise on fauna are mitigated in similar ways that traffic noise is mitigated for people, namely with noise walls or soil berms[80]. Road noise can also be mitigated through the type of pavement used, however, wear and re-sealing of the road surface over time may reduce the effectiveness of this approach. Vehicle and train noise can also be managed by reducing travel speeds and decreasing the severity or amount of braking and acceleration.

Noise walls can also function as fauna exclusion fencing and their effectiveness depends on the placement and design of the noise wall. For example:

- Noise walls on one side of the road or railway may increase fauna mortality if fauna get trapped and are unable to fully cross over.

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[78] (Zuberogoitia et al. 2015, Hu et al. 2020)
[79] (Zuberogoitia et al. 2015)
[80] (Blackwell et al. 2015, Parris 2015)

- Tall noise walls may act as flight diverters and decrease mortality for birds that fly up and over the road or railway and above vehicles, and simultaneously create a more severe barrier for low-flying birds.
- Noise walls will increase the barrier effect for gliders if they disrupt their glides, and all noise wall designs must consider the glide angles of relevant species and ensure they do not affect glider movement.

General guidelines for noise mitigation:

- Where required for species that are sensitive to the impacts of noise, noise levels should be reduced to ~55-60 dB(A)[81]. Chapter 4 describes the evidence for this threshold and further research is required to confirm these values for Queensland species.
- Consider the material used for noise walls as transparent or reflective material presents a collision risk for birds but light penetration through the noise walls may be required for safety and to avoid shading.
- Noise walls should typically be installed on both sides of the road or rail, or if on one side only, be matched with fauna fencing on the opposite side (Section 13.1).
- Designs that allow fauna to escape should be considered for long installations of noise walls (Section 15).
- The noise wall should be designed according to the needs of the target species. For example, the brackets used to attach noise panels to posts were modified to prevent koalas from climbing them (Chapter 5, Section7).

19.5 Mitigating artificial light at night

The impacts of ALAN on fauna are significant (Chapter 4) and can be minimised by only installing lighting for user safety. Lighting within or on crossing structures should be avoided as it can reduce rates of use[82].

Where required, the lighting should be in accordance with the *National Light Pollution Guidelines for Wildlife*[83] and minimised through:

- Using the lowest intensity lighting possible.
- Using sensors or timers to only provide lighting when required, such as when pedestrians or motorists are present.
- Turning off lights at times of year when susceptible species are present.
- Keeping lights as close to the ground as possible to direct light to areas that require lighting.
- Using shielding of light fixtures or light walls to minimise light spill into sensitive areas, for example, crossing structures and entrances to crossing structures.

[81] (Dooling and Popper 2007)
[82] (e.g. Bhardwaj et al. 2020)
[83] (DCCEEW 2023)

- Using 'warmer' colours of lighting rather than 'blue-white' colours.
- Dense vegetation can reduce the amount of light spill but should only be considered as a secondary or additional measure because plant senescence, death or pruning may reduce effectiveness.

The installation of streetlighting to enable motorists to detect fauna on the roadside and stop or swerve to avoid collision is not an effective strategy to reduce WVC. This is because the significant negative impact of streetlighting on space-use by all fauna is likely to far outweigh the marginal reduction in rate of WVC for a small number of species that a small number of motorists are likely to attempt to avoid.

19.6 Traffic calming

Traffic dynamics play a major role in WVC. Vehicle speed directly impacts driver reaction times and stopping distance and slower vehicle speeds can reduce the rate of WVC and fauna mortality, as well as the severity of outcomes for motorists.

Traffic calming is the process of managing the speed, timing, and/or volume of traffic on a road to reduce the rate and/or severity of WVC. However, motorists typically drive at the design speed of the road and forcing drivers to drive more slowly without changing the design of the road is very difficult. Speed reductions could be targeted at high incident areas or timed to coincide with biological events such as time of day (e.g. dawn and dusk) and breeding or migration events when fauna are likely to access the road. However, trials of reducing vehicle speed from 80-60 km/h in the evenings did not result in detectable reductions in koala-vehicle collisions or the survival of koalas after WVC over a four year study near Brisbane (Case Study 13.1).

Nevertheless, modelling has predicted that traffic calming can reduce rates of WVC[84] and further scientifically robust trials are required to investigate the effectiveness of this approach further.

Temporary or permanent road closures are potentially feasible where alternative routes with lower risk of WVC exist or can be developed.

There are very limited opportunities for traffic calming on high-speed arterial roads because they are designed for high speeds and high volumes, and slower speeds may result in traffic jams and collisions. Nevertheless, even minor improvements in the rate of WVC may be significant and WVC hot-spot data can be considered by an engineer undertaking speed limit reviews. Reducing the speed of trains in high-risk areas and/or at high-risk times may be feasible.

19.7 Signage

Wildlife warning signs are intended to modify driver behaviour by warning them of an increased risk of WVC or advising of enforced or recommended reductions in speed. There are three types of fauna warning signs used on roadsides: standard, enhanced, and temporal[85]. There are strict guidelines on the design, position, and number of signs that can be installed – refer to Queensland *Manual of Uniform Traffic Control Devices* Part 2, Section 4.11.6 and Appendix H.

[84] (van Langevelde and Jaarsma 2009)
[85] (Huijser et al. 2015)

Standard signs are typically the same style and dimensions as other roadside warning signs, and in Queensland are often a stylised black animal on a yellow background (Figure 17.1 and Figure 18.3). Enhanced signs may be larger than standard signs and include flashing lights, and/or disturbing images or text designed to grab the driver's attention, such as real-time data on the number of WVC in the area. Temporal signs operate at certain times of the day (dawn or dusk) or year (migration season) and warn motorists of a heightened risk of WVC. Enhanced signs may also be vehicle-activated and only turn on as vehicles approach.

Standard signs are commonly used around the world, but they have little to no effect on vehicle speed[86]. It has been hypothesised that most drivers do not modify their behaviour in response to standard signs because they rarely see fauna and therefore do not trust or believe the sign. In addition, the widespread deployment of standard signs in areas with few fauna reinforces this perception, thereby minimising effectiveness everywhere, including in high-risk areas.

Transport and Main Roads does not recommend standard signage alone as an effective, long-term solution to WVC.

Enhanced signs and signs that apply at specific times of the day or year, including temporary or mobile variable message signs may reduce vehicle speed slightly because the information is targeted to a species, specific to an area, and only operate when the risk of fauna vehicle collision is high. For example, enhanced signs with real-time data on the rate of fauna vehicle collision on a stretch of road would explicitly inform drivers of the actual number of collisions and reinforce the high risk of collision and may illicit a greater response[87]. Animal detection systems can also be used to activate enhanced signs (Section 19.8).

Road stencilling and pavement markings (Figure 19.7(a)) are a form of signage and designed to alert drivers with a novel approach.

Figure 19.7(a) – Standard roadside wildlife warning sign

Source: © State of Queensland

[86] (Huijser et al. 2015)
[87] (Bond and Jones 2013)

Figure 19.7(b) – Enhanced roadside wildlife warning sign, erected for a few weeks per year on Phillip Island, Victoria, when short-tailed shearwaters are fledging.

Source: © Rodney van der Ree, WSP

Figure 19.7(c) – Road stencilling in Brisbane warning motorists of the risk of WVC

Source: © Rodney van der Ree, WSP

Figure 19.7(d) – Variable message board used temporarily during koala breeding season, Peak Downs Highway, Queensland

Source: © State of Queensland

19.8 Animal detection systems

Animal detection systems are vehicle-based or road / railside-based devices that detect the presence of fauna and alert motorists and/or fauna, thereby reducing the risk of WVC[88]. Fauna are detected using a range of technology, including 'break the beam' and other sensor types, and motorists or train drivers are alerted via enhanced warning signs (Section 19.7) or in-car / train messaging.

Road or railside detection systems targeting ungulates and large carnivores are being tested in North America and Europe[89], however they have not been trialled on transport infrastructure in Australia. However, a number of proof-of-concept trials are underway in Australia, with some confirming the approach has potential applications in the future[90]. A promising approach is in areas where fauna are funnelled by fencing to a specific location where they can cross the road or railway 'at grade', and thus the warning to motorists and train drivers is applied to a specific area (i.e. at-grade crossings, Section 12).

Animal detection systems are only suitable in certain situations[91], including:

- Where sudden reductions in vehicle speed in response to detected fauna do not result in increased risk of collision with other vehicles.
- Roads and railways with relatively low traffic volume, particularly at times when the target species are likely to be moving.
- Railways where the train can feasibly slow down when approaching the area.

[88] (Huijser et al. 2015)
[89] (Huijser et al. 2009, Huijser et al. 2017)
[90] (Zhou and Xing 2023)
[91] (Huijser et al. 2015)

- Areas with the necessary power supplies to operate the system, however reliable stand-alone solar powered units are being developed.
- Areas with topographical conditions that allow the system to detect fauna and alert motorists and train drivers.
- Where the target species is large enough to be detected by the sensor.
- Where the vegetation along the road or railway does not interfere with the sensor system.

19.9 Predator control

Transport projects in areas with threatened species of fauna that are impacted by introduced predators should consider implementing a co-ordinated and integrated predator control program. Reducing predation pressure can help to lessen the impacts of habitat clearing and the overall transport project on fauna. Koalas are particularly at risk of attacks from wild dogs[92] and small mammals at risk from fox predation, and predator control should be considered for them.

Predator control should commence before clearing occurs and continue throughout construction to reduce predation pressure in habitats within and adjacent to the project area. The overall objective is to help mitigate the potential impacts of the transport project by increasing the size of the population of fauna and thus enhance population viability, enabling it to cope with the impacts of the project.

A predator control program should:

- Specify target species and predator reduction targets.
- Control methods should be consistent with current best-practice and local laws (e.g. some methods cannot be implemented in urban areas due to the presence of domestic dogs and cats).
- Be integrated and co-ordinated with other control programs that are occurring in the area.
- Include a monitoring and evaluation program (Chapter 3) to assess the success of the program.
- Undertake annual review of targets, methods, and effectiveness to inform adaptive management.

[92] (Lunney et al. 2007, Lunney et al. 2023)

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