

1 *Published version available <http://www.publish.csiro.au/paper/WR14067.htm>*

2 *Wildlife Research - <http://dx.doi.org/10.1071/WR14067>*

3 *Submitted: 9 April 2014 Accepted: 10 May 2015 Published online: 26 June 2015*

4 **Monitoring the use of road-crossing structures by arboreal marsupials: insights gained**
5 **from motion-triggered cameras and passive integrated transponder (PIT) tags**

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12 **Running head:** Monitoring arboreal mammal crossing structures

13 **Key words:** Canopy bridge, glider pole, habitat fragmentation, barrier effect, road mitigation,
14 connectivity, monitoring, individual identification

15 **Abstract**

16 *Context:* Wildlife crossing structures are installed to mitigate the impacts of roads on animal
17 populations, yet little is known about some aspects of their success. Many studies monitor the
18 use of structures by wildlife, but studies that also incorporate individual identification methods
19 can offer additional insights into their effectiveness.

20 *Aims:* We monitored the use of wildlife crossing structures by arboreal marsupials along the
21 Hume Freeway in south-east Australia to: 1) determine the species using these structures and
22 their frequency of crossing; 2) determine the number and demographic characteristics of

23 individuals crossing; and 3) use the rate of crossing by individuals to infer the types of
24 movement that occurred.

25 *Methods:* We used motion-triggered cameras to monitor five canopy bridges and fifteen glider
26 pole arrays installed at thirteen sites along the Hume Freeway. The five canopy bridges were
27 also monitored with PIT tag readers to identify the rate of use by individuals.

28 *Key results:* Five species of arboreal marsupial were detected using canopy bridges and glider
29 poles at eleven sites. Our analysis suggested that increasing the number and the distance
30 between poles in a glider pole array reduced the rate of use by squirrel gliders. The PIT tag and
31 camera footage revealed that the structures were used by adult males, adult females and
32 juveniles, suggesting that all demographic groups are capable of using canopy bridges and
33 glider poles. At two canopy bridges multiple squirrel gliders and common brushtail possums
34 crossed more than once per night.

35 *Conclusion:* Given that previous studies showed that the freeway was a barrier to movement,
36 and that many of the species detected crossing are subject to road mortality, we conclude that
37 canopy bridges and glider poles benefit arboreal marsupials by providing safe access to
38 resources that would otherwise have been inaccessible.

39 *Implications:* While the factors influencing crossing rate require further study, our analysis
40 suggests that glider pole arrays with fewer poles placed closer together are likely to be more
41 successful for squirrel gliders. The individual identification methods used in this study offer
42 insights that are not possible from measuring the rate of use alone and should be adopted in
43 future monitoring studies.

44

45 **Introduction**

46 Roads and traffic form barriers to animal movement when animals are unable to cross due to
47 physical or behavioural limitations, or when those attempting to cross are killed by vehicles
48 (Bennett 1991; Burnett 1992; Goosem 2001; Oxley et al. 1974). This process sub-divides habitat
49 creating smaller, isolated populations with a higher risk of local extinction (Bennett 1991;
50 Fahrig and Rytwinski 2009; Forman et al. 2003; van der Ree et al. 2015b). Road agencies often
51 install wildlife crossing structures (e.g. culverts, tunnels, land bridges) to mitigate these effects
52 and conserve roadside populations (Forman et al. 2003; Taylor and Goldingay 2010; van der
53 Grift et al. 2013; van der Ree et al. 2007). Given the financial investment in crossing structures
54 worldwide, and their use to meet environmental regulatory requirements, it is critical that we
55 understand how well they work.

56 Many studies use cameras to monitor the use of crossing structures by wildlife and infer the
57 effectiveness of the structures, or particular design features, based on how frequently animals
58 use them (e.g. Clevenger and Waltho 2000; Grilo et al. 2008; Ng et al. 2004; van der Ree et al.
59 2007). However, few studies identify and record the number of individuals that use a structure
60 (but see Baxter-Gilbert et al. 2013; Boarman et al. 1998; Chambers and Bencini 2015; Clevenger
61 and Sawaya 2010; Dodd et al. 2007; Harris et al. 2010). Knowing the number and type of
62 individuals crossing adds value to a monitoring program for two reasons. First, it can show
63 whether a structure is used by all types of individuals or just a small subset of the population
64 and whether demographic connectivity (i.e. affecting recruitment and reproductive rates) is
65 facilitated. For example, if a crossing structure only benefits a small proportion of the local
66 population, or use is dominated by one gender or age-class, then the structure is unlikely to
67 facilitate demographic connectivity (Clevenger 2005; Herrod 2005; Olsson et al. 2008). Second,
68 crossing structures, like corridors, may facilitate multiple types of movement, which can be
69 categorised by different patterns of use. Movements to access resources within an animal's
70 home-range are generally short and frequent, while dispersal movements over long distances

71 tend to be infrequent or seasonal (Bennett 1999; Bissonette and Adair 2008; Van Dyck and
72 Baguette 2005). These different types of movement can potentially be determined by
73 identifying the individuals that use the crossing structure. For example, a camera may detect 20
74 crossings in a night, but only methods that identify individuals can reveal if the structure was
75 used by 20 individuals crossing once each or a single individual crossing 20 times. This
76 information can give valuable insights into how a crossing structure might benefit a population,
77 e.g. through occasional dispersal or regular habitat access (Clevenger 2005; Foster and
78 Humphrey 1995; van der Ree et al. 2007; van der Ree et al. 2009). Monitoring use is an
79 important first step in evaluating the effectiveness of wildlife crossing structures and by making
80 these initial studies more informative, they can better guide and complement future population-
81 level studies (Soanes 2014; van der Grift et al. 2013; van der Grift and van der Ree 2015).

82 Canopy bridges and glider poles (hereafter referred to as 'bridges' and 'poles') are crossing
83 structures installed around the world to mitigate the impacts of roads on arboreal mammals
84 (Goldingay et al. 2013; Kelly et al. 2013; Mass et al. 2011; Soanes et al. 2013; Soanes and van der
85 Ree 2015; Taylor and Goldingay 2012b; Teixeira 2013; Weston et al. 2011). In eastern Australia,
86 road agencies increasingly rely on bridges and poles to mitigate the impacts of major roads on
87 threatened arboreal marsupials, including the squirrel glider (*Petaurus norfolcensis*). In the
88 absence of crossing structures, major roads create a barrier to glider movement and reduce the
89 survival rate and viability of squirrel glider populations (McCall et al. 2010; Taylor and
90 Goldingay 2012a; van der Ree et al. 2010). Canopy bridges and glider poles were installed along
91 a freeway in south-east Australia to provide safe passage for squirrel gliders and other arboreal
92 marsupial species. The effectiveness of these structures has yet to be determined. We
93 monitored the use of canopy bridges and glider poles by arboreal marsupials with the following
94 aims:

95 1) to determine the species using these structures and their frequency of crossing;

- 96 2) to determine the number and demographic characteristics of individuals crossing
97 canopy bridges; and
- 98 3) to use the rate of crossing by individuals to infer the types of movement that occurred
99 across canopy bridges.

100

101 **Methods**

102 *Study area*

103 The Hume Freeway is a major interstate freeway in south-east Australia that has been
104 progressively upgraded to a four-lane, divided freeway over the past 50 years. The width of the
105 freeway from road edge to road edge varies from 40 to 80 m, depending on the width of the
106 centre median, which ranges from 21 to 38 m. Each carriageway is 12 m wide (including
107 emergency and travel lanes). The treeless gap across the Hume Freeway can exceed 100 m
108 where mature trees have been cleared from the centre median and roadsides, presenting a
109 barrier to the movement of arboreal marsupials. We studied two sections of freeway located
110 approximately 200 km apart; a length of 63 km in the state of Victoria between the towns of
111 Avenel and Benalla that was upgraded in the 1970s-80s, and a length of 70 km in the state of
112 New South Wales between the towns of Albury and Tarcutta that was upgraded in 2009 (Figure
113 1). The traffic volume averages 10,000 vehicles per day at a maximum legal speed of 110 km/h
114 (DOTARS 2007). The landscape surrounding the Hume Freeway is predominantly agricultural
115 land and rural townships, with remnant and regrowth woodland occurring only in small
116 patches, travelling stock reserves (TSRs) and linear reserves as described in van der Ree (2002)
117 and Gibbons and Boak (2002).

118 [Figure 1]

119 *Study species*

120 The patches of *Eucalyptus* spp. woodland along the Hume Freeway are a critical resource for
121 arboreal marsupials including: the squirrel glider; the sugar glider (*Petaurus breviceps*); the
122 common brushtail possum (*Trichosurus vulpecula*); the common ringtail possum (*Pseudocheirus*
123 *peregrinus*); the brush-tailed phascogale (*Phascogale tapoatafa*); the yellow-footed antechinus
124 (*Antechinus flavipes*), and; the koala (*Phascolarctos cinereus*). While all of these species can be
125 negatively affected by roads (e.g. Dique et al. 2003; Gulle 2006; Herrod 2005; Russell et al.

126 2009) the squirrel glider was the primary target of mitigation and monitoring. Listed as
127 Threatened in Victoria and Vulnerable in New South Wales (Claridge and van der Ree 2004; DSE
128 2007), squirrel gliders move by gliding from tree to tree with an average glide length of 30–40
129 m, although glides of up to 70 m have been recorded (Jackson 2000; van der Ree et al. 2003; van
130 der Ree et al. 2010).

131 *Wildlife crossing structures*

132 Crossing structures were installed where the Hume Freeway intersected mature woodland
133 habitat and was likely to limit squirrel glider movement. That is, at sites where squirrel gliders
134 were not expected to be able to safely cross the freeway using existing roadside trees (12–25 m
135 tall) based on a glide ratio of 2.5:1 (Jackson 2000; van der Ree et al. 2010). The width of the
136 treeless gap created by the freeway ranged from 60–380 m (Table 1). Previous studies show
137 major roads with a treeless gap of > 50 m wide restrict squirrel glider movement (Soanes et al.
138 2013; van der Ree 2006; van der Ree et al. 2010). In 2007, crossing structures were retrofitted
139 to five sites in Victoria. A further eight sites in New South Wales were mitigated during the
140 freeway upgrade in 2009. The number of structures required at each site varied (between one
141 and three) depending on the extent and configuration of roadside habitat (Table 1).

142 [Figure 2]

143 Canopy bridges were made of UV-stabilised marine-grade rope (~15 mm diameter) woven into
144 a flat net 50 cm wide, resembling a long, narrow strip of cargo net. Two steel cables suspended
145 the rope between hardwood timber poles on either side of the freeway. Four bridges, ranging
146 from approximately 60 to 85 m long, were erected at a minimum of 6 m above the road (Figure
147 2). A fifth bridge (Yarra Yarra Creek), 170 m long (zig-zagged across a gap of ~150 m), was
148 installed under an open-span road bridge at a minimum height of 4 m from the ground and 2 m
149 from the underside of the bridge and was supported by six poles along its length. Canopy
150 bridges were installed as close as possible to the existing roadside woodland, usually within 5 m

151 of overhanging tree branches (up to 15 m from tree trunk). Additional ropes connected the ends
152 of each canopy bridge to the branches of roadside trees to facilitate access by arboreal
153 marsupials (1 to 3 ropes per end).

154 Glider poles (round, hardwood timber poles ~13–18 m tall, 40–50 cm in diameter) provide
155 gliders with an alternative glide site to reduce the width of the treeless gap across the road
156 (Soanes and van der Ree 2015). A timber cross-beam (10 cm x 10 cm x 2.4 m) was fixed
157 horizontally 50 cm from the top of each pole (oriented parallel to the road edge) providing a
158 'branch-like' launch site. The number and height of poles required depended on the width of the
159 gap across the freeway and the height of roadside trees relative to the height of the road (i.e. if
160 road was in a cutting or raised). As such, each pole crossing could include a single pole in the
161 centre median, or an array of multiple poles placed in the median and roadsides (Figure 2, Table
162 1). Glide paths were calculated in detailed schematics to ensure that glides in each direction
163 were achievable within a recommended glide ratio of 2.5:1, allowing animals to pass safely
164 above the maximum expected height of traffic. These designs took into account the terrain and
165 the height and location of roadside trees to determine the appropriate height and spacing of
166 glider poles in each array (e.g. Soanes and van der Ree 2015). Squirrel gliders and sugar gliders
167 were the only species within the study area capable of using glider poles to cross the freeway.

168 *Monitoring crossing structures*

169 We used two methods to monitor the use of crossing structures by arboreal marsupials; motion
170 triggered, infrared cameras (Orion, Buckeye Pty Ltd) and PIT tag reading systems (Trovan,
171 Microchips Australia Pty Ltd). Cameras were installed on all crossing structures. PIT tag readers
172 were only placed on canopy bridges, as a suitable design for glider poles was not available.
173 Equipment was installed between April and June 2012 and the structures were monitored until
174 February 2013, providing 9–11 months of monitoring per structure. This period occurred
175 approximately five years after the crossing structures were installed in Victoria and three years
176 after crossing structures were installed in New South Wales. The number of possible monitoring

177 nights per structure ranged from 258 to 315, however, due to equipment malfunctions, the
178 actual monitoring effort ranged from 75 to 279 nights per structure (Table 2). Detail on the
179 monitoring set-up for each method is described below.

180 [Table 2]

181 Motion triggered cameras

182 We placed one camera at each end of each bridge (i.e. two cameras per bridge), and one on the
183 centre median pole of each glider-pole array. At bridges, cameras were triggered by animal
184 movement past a pair of active infrared sensors placed approximately 1 and 4 m from each
185 camera. At poles, cameras were mounted on one end of the cross-beam, so that animals moving
186 along the length of the beam or to the top of the pole would trigger the passive infrared sensor.
187 Each time a sensor was triggered the cameras recorded 9–20 seconds of video. Cameras were
188 powered by an appropriately sized lead-acid battery and solar panel.

189 Videos from the Victorian structures were transmitted wirelessly to the memory card of an on-
190 ground unit from where they were downloaded during fortnightly field visits. Cameras on the
191 New South Wales structures used an internal modem to transmit videos to the office computer
192 each morning via the 3G mobile phone network. We inspected all videos for the presence of
193 animals on bridges and poles. Each time an animal was detected, the date, time and species
194 were recorded, as well as the number of videos the animal appeared in and direction of travel.
195 Where observed, distinctive markings such as male scent glands, ear notches, or differences in
196 body size were noted to determine the animal's approximate age and sex.

197 At bridges, the placement of a camera at each end of the bridge allowed us to confirm crossings.
198 A crossing was confirmed when an animal was viewed moving out onto the bridge by one
199 camera and away from the camera until it was out of sight, then detected by the camera on the
200 opposite side of the bridge and viewed exiting the structure. When only one camera was
201 operational, crossings were inferred based on the animal's behaviour and direction of travel.

202 For example, if an animal moved out onto the bridge (i.e. approaching the other side) until it
203 was no longer visible and did not turn around and return within ten minutes we classified it as a
204 crossing. This is based on the fact that more than 90% of crossings confirmed by both cameras
205 were completed in less than ten minutes. In this way, we distinguished crossings from 'visits', in
206 which an animal was detected moving on to the bridge before turning around and exiting the
207 same side without completing the crossing.

208 Crossings could not be confirmed at glider poles. Animals can glide to the pole in the centre
209 median from any number of roadside trees (or roadside poles) and land on the pole below the
210 cross-arm, out of view of the camera. This means that it is impossible to determine the direction
211 of travel. While we acknowledge that some animals may glide to the centre median pole and
212 then return to the same side, we expect this to represent only a small proportion of detections,
213 as there is no habitat in the centre median and therefore no reason for animals to repeatedly
214 glide to the centre pole without completing the crossing. This is supported by previous
215 radiotracking data, which showed that individuals detected on the centre median pole went on
216 to cross the freeway (Soanes et al. 2013). Therefore, we refer to all detections on the centre
217 median pole as crossings for the purposes of this study. However this may overestimate the true
218 number of complete crossings where squirrel gliders glide to the centre median pole and return
219 without crossing.

220 Preliminary analysis of factors affecting crossing rate

221 Site covariates and design attributes of the road and crossing structures can influence the use of
222 crossing structures by wildlife. For each site, the road width (width of the treeless gap across
223 the road as measured from trunk to trunk), the distance of the structure to roadside trees,
224 bridge length, number of poles in a glider pole array and maximum glide distance (between two
225 successive poles or pole and tree in an array of poles) were obtained from schematic diagrams,
226 satellite imagery and site visits (Table 1). We also calculated an activity index for squirrel
227 gliders (the target species) using data from a concurrent mark-recapture study to estimate the

228 number of individuals that were active in the habitat adjacent to the mark-recapture study. The
229 activity index was determined at the site level by dividing the average minimum number of
230 squirrel gliders known to be alive (MNKTBA) by the area of habitat trapped at each site (details
231 provided in Appendix 1).

232 Upon inspection of the data it became clear that it would not be possible to investigate all
233 potential factors influencing crossing rates within the scope of this study. There were only five
234 canopy bridge sites available, and of these only three were used by arboreal marsupials. This
235 sample size was not suited to further statistical analysis, and so we limited our analysis to glider
236 poles. As non-gliding species were restricted to using canopy bridges, and sugar gliders were
237 detected at only three sites, we further restricted our analysis to squirrel gliders. At the time of
238 this study, two glider pole arrays at Kyeamba TSR were >100 m from the nearest roadside
239 squirrel glider habitat, as the habitat restoration works activities surrounding the structures
240 have not yet successfully linked the crossing structure with the existing roadside trees. This
241 distance is well beyond the maximum glide range of a squirrel glider, and therefore we excluded
242 these two structures from further analysis. This left us with a sample size of 13 glider poles to
243 include in statistical analysis.

244 Due to the limited dataset we restricted our analysis to two factors likely to influence the use of
245 glider poles by squirrel gliders: the number of poles in an array (hereafter 'number of poles'),
246 and the maximum glide distance required to cross the glider pole array (hereafter 'glide
247 distance'). We chose to focus on these factors because they are both biologically meaningful and
248 also relevant to managers as these design features are relatively easily to manipulate when
249 installing crossing structures. We did not include the activity index as a parameter, as
250 preliminary analysis revealed that its effect on crossing rate was highly uncertain. Inspection of
251 the data showed that a high activity index did not correspond with a high crossing rate at that
252 site. Further, multiple structures from the same site and hence the same activity index
253 commonly varied widely in crossing rates.

254 We used a Poisson regression to investigate the effect of glide distance and the number of poles
255 on the crossing rate. The data used to estimate the model parameters were the number of
256 crossings observed within each of 26 time periods of varied length during which the cameras
257 were operating. The expected number of crossings per night was modelled as the exponent of a
258 linear model with a grand mean, and fixed effects for the number of poles and glide distance.
259 Error terms were included to account for residual error and a random effect of each individual
260 crossing structure on the crossing rate. The model was estimated using Bayesian inference in
261 the program OpenBugs 3.2.1 (Spiegelhalter et al. 2011). We used vague priors for all
262 parameters, using a normal distribution with a mean of 0 and a standard deviation of 1000 for
263 the fixed effects and half-Cauchy distributions with scale 25 for the random effects (Gelman
264 2006). The model code and data are provided in Appendix 2. The model was run for 50,000
265 iterations after discarding a burn-in of 20,000. Convergence was assessed through the visual
266 inspection of three independent chains.

267 PIT tag scanners on canopy bridges

268 We installed one flat panel antenna (ANT-612, Trovan, Microchips Australia Pty Ltd, Figure 3.2)
269 at each end of each canopy bridge (i.e. two antennae per bridge). Antennae were approximately
270 the same width as the bridge (40 cm) with a read distance of 35 cm. Data were stored in an
271 attached decoder unit (LID650, Trovan, Microchips Australia Pty. Ltd.) fixed to the support pole.
272 The antennae were not continuously operational due to constraints on the size of the battery
273 and solar panel that could be installed on canopy bridges. Antennae on bridges in New South
274 Wales were integrated with the camera's active infrared sensors and only operated when a
275 sensor was triggered. In Victoria, we could not integrate antennae with the existing camera
276 sensors and therefore we scheduled them to operate for half of the night. At these bridges one
277 antenna was operational from 17:00 h until 23:59 h and the opposite from 00:01 h until 07:00
278 h. A full night of monitoring was achieved if both antennae were operational on the same night.
279 Unfortunately, the units frequently malfunctioned and a full night of monitoring only occurred

280 on 32 nights at the Longwood bridge and four nights at Violet Town. On all other nights the
281 Victorian bridges were only monitored with one antenna (6–7 hours per night), leaving
282 approximately 3–6 hours of the night unmonitored depending on the season, therefore our
283 study is likely to underestimate the true number of individuals that used the canopy bridges.

284 Data from the Victorian PIT tag readers were downloaded from the decoder via a USB cable
285 during fortnightly site visits. Decoders on bridges in New South Wales contained modems
286 programmed to transmit data to the office computer each morning via the 3G mobile phone
287 network. We recorded the time and date of each PIT tag reading and matched it with the
288 corresponding video where possible. PIT tag readings were also cross-checked against mark-
289 recapture records to identify each individual. Unless both PIT tag antennae at a bridge were
290 simultaneously operational, it was not possible to confirm crossings using PIT tags alone.
291 Therefore we cross-checked the time and date of all tag reads with the videos recorded by
292 cameras to collect information on the crossing behaviour of tagged individuals.

293 Mark-recapture surveys were also conducted at all five canopy bridge sites (as described in
294 Appendix 1). All squirrel gliders and common brushtail possums captured were implanted with
295 a PIT tag under the skin between the shoulder blades (ID 100, Trovan, Microchips Australia Pty
296 Ltd). Data from the existing mark-recapture data set suggests that the rate of tag loss is <0.05%
297 (unpublished data), which corresponds to other studies on small mammals (Schooley et al.
298 1993). Other species were not marked with PIT tags, as they are rarely captured in wire cage
299 traps. The average MNKTBA for common brushtail possums and squirrel gliders in habitat
300 adjacent to each canopy bridge site was calculated as described for glider poles (Appendix 1,
301 Table 1, Table 6).

302 **Results**

303 *Rate of use by arboreal marsupials*

304 Using motion-triggered cameras, we detected five species of arboreal marsupial using both
305 types of crossing structure over 3,929 nights of camera monitoring: squirrel gliders ($n=1,317$
306 detections), common ringtail possums ($n=394$), common brushtail possums ($n=241$), sugar
307 gliders ($n=258$) and brush-tailed phascogales ($n=4$) (Tables 3 and 4). Only 42 detections were
308 classed as visits and excluded from further analysis. No koalas or yellow-footed antechinus
309 were detected, despite occurring in the general area. Arboreal marsupials used crossing
310 structures to cross the freeway at 11 of the 13 monitoring sites. Two canopy bridges and four
311 glider pole arrays were not used by any species. Squirrel gliders were detected crossing the
312 road using canopy bridges and glider poles. Both species of possum and phascogales were only
313 detected crossing bridges. Sugar gliders were only detected using poles to cross the road.

314 [Table 3, Table 4]

315 The number of crossings per night varied widely among sites, with some structures used
316 frequently and others not at all (Tables 3 and 4). For example, squirrel gliders were detected
317 crossing the Longwood bridge, Warrenbayne pole, Sages pole 1 and Kyeamba Creek pole 1 more
318 than once each night, while the Violet Town bridge and Sages pole 2 were used less than once
319 every two months. Seven structures were not used by squirrel gliders, even though the species
320 was present at all sites. Therefore while the mean crossing rate for squirrel gliders was 0.84
321 crossings per night at canopy bridges (\pm SE 0.84) and 0.38 at glider poles (\pm SE 0.17), the
322 crossing rate at any one site ranged from 0.00 to 4.19 crossings per night. Crossing rates by
323 other species ranged from 0.00 to 1.14 crossings per night for common brushtail possums
324 (mean 0.23, \pm SE 0.23); 0.00 to 1.36 crossings per night for common ringtail possums (mean
325 0.46, \pm SE 0.28); and 0.00 to 0.93 crossings per night for sugar gliders (mean 0.07, \pm SE 0.06).
326 Brush-tailed phascogales were detected infrequently on one bridge, with 1 crossing per 50
327 nights of monitoring (0.02 crossings per night).

328 The regression analysis revealed that the number of poles in a glider pole array and the
329 maximum glide distance required to cross had a negative effect on the use of glider poles by

330 squirrel gliders. The point estimates for the effect of number of poles and glide distance were
331 both negative (-1.26 and -0.12, respectively), although the credible intervals for both
332 parameters overlapped zero reflecting uncertainty in the estimates, and rather more so for the
333 distance than number of poles (Table 5). The wide credible intervals are not surprising given
334 the low sample size available for analysis ($n=13$). Based on these data, the predicted mean rate
335 of use for a glider pole array consisting of two poles with a maximum distance of 30 m apart
336 was 0.11 crossings per night (95% CI 0.00–0.53). Note that this does not predict beyond the
337 observed data and does not incorporate possible sources of uncertainty.

338 [Table 5]

339 The video footage showed that multiple individuals of both sexes used the crossing structures,
340 including adults and juveniles. This finding was based on observed differences in body size, the
341 presence of active scent glands and ear notches visible in 445 of the 2,291 of the occasions
342 during which animals were detected. Both species of possum were observed carrying
343 dependent young across the Longwood and Violet Town canopy bridges and adult squirrel
344 gliders were seen carrying pouch young or accompanied by smaller individuals, presumably
345 juveniles, on poles (Figure 3). Independent juveniles (i.e. not carried by parents) were also
346 observed, with juvenile ringtail possums at the Violet Town bridge, and juvenile squirrel gliders
347 at Kyeamba Creek pole 2, Sages pole 2, and the Warrenbayne and Blue Metal poles.

348 *Rate of use by individuals*

349 Three squirrel gliders and five common brushtail possums with PIT tags were detected crossing
350 two canopy bridges over the 11 months during which PIT tag readers were in use. Three
351 squirrel gliders and a common brushtail possum were detected crossing the Longwood bridge
352 and four common brushtail possums were detected crossing the Violet Town bridge. A fourth
353 squirrel glider was detected on the canopy bridge at Sages TSR but did not complete the
354 crossing. All individuals were reproductively active adults. Due to equipment malfunctions, only

355 5–27% of detections by PIT tag reader could be confirmed as crossings. However, given that
356 only 42 of the 1,112 camera detections at bridges were identified as visits, we are confident that
357 a large portion of the detections by the PIT tag reader also represent complete crossings. The
358 number of individuals observed using the canopy bridges was generally lower than the number
359 present in the surrounding habitat (as indicated by the average MNKTBA), with the exception of
360 the bridge at Longwood, where the number of squirrel gliders observed crossing was
361 approximately equal to the average MNTKBA (Table 4). Canopy bridges at Yarra Yarra Creek,
362 Blue Metal TSR and Sages TSR were not crossed by any tagged squirrel gliders or common
363 brushtail possums despite the presence of tagged individuals in the adjacent habitat (Table 4).

364 **Discussion**

365 *Use of structures by arboreal marsupials*

366 Five species of arboreal marsupial were detected using crossing structures to cross the Hume
367 Freeway, including structures that were retrofitted to existing sections of the freeway and those
368 that were installed during freeway construction. Squirrel gliders, common brushtail possums,
369 common ringtail possums, sugar gliders and brush-tailed phascogales are all affected by road
370 mortality (pers. obs.; McCall et al. 2010; Russell et al. 2009; Taylor and Goldingay 2004) and
371 structures that increase their safe passage across the road may help reduce rates of road-kill.
372 There is now mounting evidence that canopy bridges and glider poles of various designs are
373 used by a wide range of arboreal mammals, including monkeys, lemurs, and squirrels
374 (Donaldson and Cunneyworth 2015; Goldingay et al. 2013; Kelly et al. 2013; Mass et al. 2011;
375 Soanes et al. 2013; Taylor and Goldingay 2012a; Teixeira 2013; Weston et al. 2011) and these
376 structures are likely to be useful for other species with similar behaviours and ecological
377 requirements, including arboreal reptiles and amphibians. For example, mahogany gliders
378 (*Petaurus gracilis*), mountain brushtail possums (*Trichosurus cunninghami*) and western ringtail
379 possums (*Pseudocheirus peregrinus occidentalis*) have similar ecology and behaviour to species

380 detected in this study and are negatively affected by roads and fragmentation (Asari et al. 2010;
381 Taylor and Goldingay 2004; Trimming et al. 2009).

382 While small sample sizes limited the statistical analysis possible within this study, we were able
383 to identify some general principles for the design of crossings structures for arboreal
384 marsupials. Arboreal marsupials used all structure types monitored in this study, including
385 bridges up to 85 m long and roadside glider pole arrays consisting of up to four poles. While no
386 animals were detected using the under-road canopy bridge in our study, previous work by
387 Goldingay et al. (2013) detected common brushtail possums, common ringtail possums and
388 feathertail gliders (*Acrobates pygmaeus*) using an under-road bridge, suggesting that this design
389 is also useful. Our analysis suggests that the use of glider pole arrays by squirrel gliders
390 decreases as the number of poles and the distance between the poles increases. This is
391 supported by studies of glide capacity, which show that glide success decreases as glide distance
392 increases (Ball and Goldingay 2008; Goldingay and Taylor 2009; Jackson 2000; van der Ree et
393 al. 2003). Though we could not analyse it in our study, a similar principle is likely to apply to
394 canopy bridges, with shorter spans likely to be more successful than longer ones, particularly
395 for species that prefer closed canopy (e.g. Goosem et al. 2006; Weston et al. 2011). Crossing
396 structures for arboreal mammals are therefore more likely to be successful if the width of the
397 treeless gap across the road is minimised during construction, or structures are retrofitted to
398 locations where the existing gap is narrowest. This will allow glider pole arrays to consist of
399 fewer poles that can be placed closer together, or shorter-span canopy bridges.

400 *Identifying the number and type of individuals*

401 Collecting data on the age and sex of the animals using crossing structures provides valuable
402 information on the ability of crossing structures to benefit the wider population (Clevenger
403 2005; Olsson et al. 2008; Sawaya et al. 2013). For example, Sawaya et al. (2013) identified eight
404 female and nine male black bears (*Ursus americanus*) using crossing structures in Banff National
405 Park, Canada and concluded that these structures provided demographic connectivity.

406 Conversely, Olsson et al. (2008) concluded a highway overpass was unlikely to affect the
407 population demographic rates of moose (*Alces alces*) populations based on the low number of
408 crossings made predominantly by males. In our study, PIT tags and body markings observed in
409 video footage revealed that males and females, including females carrying dependent young,
410 used canopy bridges and glider poles to cross the freeway. That is, no demographic group was
411 excluded from using either structure type to cross the freeway. A comparison of the crossing
412 rates obtained through video and PIT tag readers suggests that the crossing rate of common
413 brushtail possums and squirrel gliders at the Violet Town and Longwood canopy bridges was
414 almost entirely due to the repeated movements of a few individuals (1–4 individuals of each
415 species per structure). Population-level analyses are required to assess whether or not the
416 number of individuals crossing is enough to maintain demographic and genetic connectivity for
417 the wider population. However based on our findings it is unlikely that there are any features of
418 the current crossing structure designs that would prevent crossing structures from facilitating
419 demographic and genetic connectivity.

420 *Inferring types of movement*

421 Identifying patterns of use by individuals allowed us to infer the types of movement that
422 crossing structures facilitated. For example, daily movements are generally associated with
423 foraging and accessing resources within an individual's home range (Bennett 1999; Bissonette
424 and Adair 2008; Van Dyck and Baguette 2005). The high average crossing rates (more than one
425 crossing per night) of squirrel gliders and common brushtail possums at canopy bridges as
426 detected by cameras, were revealed by the PIT tag reader to be 3–4 individual animals crossing
427 repeatedly (often multiple times each night). Prior to the installation of the Longwood and
428 Violet Town canopy bridges, squirrel gliders and common brushtail possums did not cross the
429 freeway regularly at these sites (Gulle 2006; Soanes et al. 2013; van der Ree et al. 2010). In our
430 study, two squirrel gliders at the Longwood bridge and one common brushtail possum at the
431 Violet Town bridge crossed almost every night, gaining nightly access to habitat on both sides of

432 the freeway. Such regular use suggests that these individuals incorporate the crossing structure
433 within their home range. Therefore it is possible that the high crossing rate at these sites is
434 driven by a few individuals frequently crossing in order to access portions of their home range
435 on either side of the road. It is likely that the high frequency of crossings (~ 1 crossing/night) by
436 squirrel gliders at glider poles such as Warrenbayne, Little Billabong, Sages TSR pole 1 and
437 Kyeamba Creek pole 1, common ringtail possums at the Violet Town bridge, and sugar gliders at
438 the Little Billabong pole also reflect repeated crossings by a few individuals. Radiotracking
439 studies that investigate home-range movements could be used to confirm this theory. Canopy
440 connectivity is critical to maintain daily movements of arboreal species that are gap-limited or
441 unwilling to cross open spaces (e.g. Anzures-Dadda and Manson 2007; Asari et al. 2010;
442 Laurance and Laurance 1999; van der Ree et al. 2010; Wilson et al. 2007). This supports the
443 idea that crossing structures can benefit wildlife by providing access to resources that would
444 have been unavailable, or dangerous to reach, if crossing structures were not present (Bennett
445 1999; Eigenbrod et al. 2008).

446 Despite the advantages of using PIT tags to identify individuals, it did not help us infer other
447 types of movement, such as dispersal, or allow us to detect effects at the population level.
448 Dispersing individuals may be sourced from a large number of source populations, and tagging
449 all potential dispersers that might use the structure would require an intensive and extensive
450 survey effort. Furthermore, movement across a structure does not necessarily result in
451 population-level effects (van der Grift et al. 2013; van der Ree et al. 2007; van der Ree et al.
452 2011). For example, territorial behaviour by resident individuals in roadside habitat can limit
453 the reproductive success of dispersing individuals, creating a social barrier to gene flow despite
454 movement (e.g. Riley et al. 2006, Corlatti et al. 2009, Simmons et al. 2010). Similarly, while the
455 detection of animals crossing suggests that those individuals crossed safely and that roadkill is
456 less likely to occur, we cannot say that population-level survival rates have improved.
457 Ultimately, mark-recapture surveys collecting information on populations size, gene flow and
458 survival rates before and after crossing structures are installed are required to determine

459 whether the patterns of crossing behaviour yield population-level benefits (Corlatti et al. 2009;
460 Sawaya et al. 2014; Simmons et al. 2010; van der Grift et al. 2013; van der Ree et al. 2007; van
461 der Ree et al. 2011).

462 *Limitations of studying arboreal crossing structures*

463 Investigating the optimal dimensions of crossing structures and factors influencing use (e.g.
464 structure placement, habitat quality and needs of the local population) guide best-practice
465 mitigation and are a critical aspect of road ecology (van der Grift and van der Ree 2015).
466 However, our study had limited statistical power due to the low replication and low crossing
467 rates by some species. Our study almost certainly underestimated the true number of crossings
468 and longer-term surveys may reveal that more of these structures are used by wildlife over time
469 (e.g. Bond and Jones 2008; Clevenger and Waltho 2003; Gagnon et al. 2011; Soanes et al. 2013).
470 While longer survey periods are likely to increase the number of crossings observed, increasing
471 the number of canopy bridges and glider poles is more difficult. It is unlikely that a study along a
472 single stretch of road, or mandated monitoring from a single construction project will have
473 sufficient replication to investigate how structural and site attributes affect rates of use for
474 different arboreal species (Rytwinski et al. 2015; van der Ree et al. 2015a). A promising avenue
475 to improve replication in future studies is for road agencies and researchers to combine
476 multiple projects into a coordinated monitoring program, thus enabling a thorough
477 investigation of the factors that influence the effectiveness of crossing structures for arboreal
478 mammals. Alternatively, the experimental manipulation of structural attributes in field trials
479 could be used to explore the optimal structure designs (Rytwinski et al. 2015; van der Ree et al.
480 2015a).

481 Monitoring arboreal crossing structures also presents a unique set of challenges when
482 compared to culverts or land-bridges (Gregory et al. 2014; Taylor and Goldingay 2014).
483 Cameras, sensors, batteries and solar panels must be securely installed 6–20 m high above an
484 active roadway (storing power sources at height reduces risk of vandalism and theft). In our

485 study, access to the monitoring equipment was only possible with an elevated work platform,
486 which requiring a licensed operator, and traffic management to close highway lanes at
487 approximately \$5,000–\$10,000AUD per day. To our knowledge, this is the first study to use
488 wireless download technology and PIT tag readers on arboreal crossing structures.

489 Unfortunately, though we tested the equipment extensively prior to its installation there were
490 several unexpected technical issues once the monitoring program was in place. Due to the
491 difficulties and costs associated with accessing the equipment, it was not feasible to conduct
492 regular repairs, leading to a loss of data at some sites. These issues should be carefully
493 considered when planning a monitoring study of arboreal structures, and additional
494 maintenance costs should be factored into monitoring budgets.

495 *Conclusions*

496 Improving the quality of information gained from monitoring studies is crucial if we are to
497 understand the conservation value of wildlife crossing structures. We found that individual
498 identification provided insights that would not have been possible through monitoring the rate
499 of use alone. While we used PIT tag readers, other methods such as non-invasive genetic
500 sampling (e.g. Sawaya et al. 2013), radio- or GPS-tracking (e.g. Dodd et al. 2007; Olsson et al.
501 2008) or coat pattern recognition (e.g. Mendoza et al. 2011; Trolle and Kery 2003) could be
502 used to obtain similar information. The most appropriate method will depend on the species
503 (e.g. not all species can be recognised by coat pattern). Canopy bridges and glider poles were
504 used by several species of arboreal marsupial, allowing safe access to resources that would have
505 been otherwise unavailable. In our study crossing structures were primarily used by a small
506 proportion of the population to regularly access habitat on both sides of the freeway. However,
507 while this benefits the small number of individuals that use the structure, it is unknown
508 whether this is enough to provide demographic or genetic connectivity for the wider
509 population. Still, if even a few dispersing individuals successfully cross and reproduce, and the
510 structures reduce rates of roadkill, then they are likely to benefit populations (Taylor and

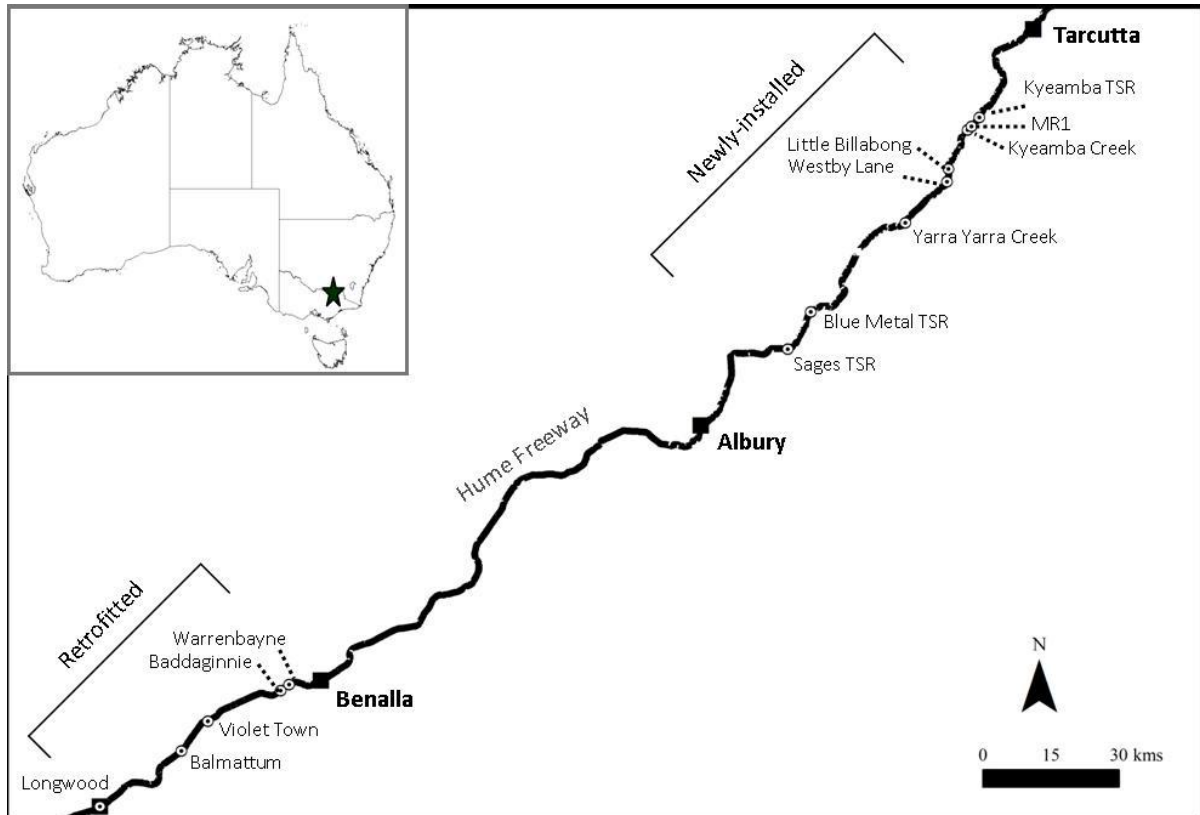
511 Goldingay 2012a). Based on this and previous studies, these structures are likely to have a
512 positive effect on a wide range of arboreal mammals, particularly gap-limited species or those
513 that are frequent victims of road mortality. Canopy bridges can benefit a wider range of species
514 than glider poles, and should be the preferred mitigation method where feasible. Methods such
515 as PIT tag readers are underutilised and should be widely adopted in studies monitoring the use
516 of structures by wildlife (Gibbons and Andrews 2004; van der Ree et al. 2007).

517 **Acknowledgements**

518 We thank The Baker Foundation, the Australian Research Centre for Urban Ecology, the
519 Australian Research Council (grant LP0560443), The Australian Research Council Centre of
520 Excellence for Environmental Decisions, the Holsworth Wildlife Research Endowment (ANZ
521 Trustees Foundation), the M.A. Ingram Trust, the RSPCA Alan White Scholarship and the
522 Wildlife Preservation Society of Australia for supporting this research. VicRoads and the New
523 South Wales Roads and Maritime Services provided invaluable financial and institutional
524 support for this project. Thanks to Doug Black, Varun Uthappa and Ross Meggs for help in
525 developing the monitoring systems. All animals in Victoria were trapped and tagged under the
526 approval of The University of Melbourne Animal Ethics Committee (1112269.1) and the
527 Department of Sustainability and Environment wildlife research permit (1006094). All animals
528 in New South Wales were trapped and tagged under the NSW Animal Research Authority (TRIM
529 09/5853) and the NSW National Parks and Wildlife Service Scientific License (S12782 and
530 SL100739). W. Sowersby, R. Soanes, L. Harrison, B. Mitchell and R. Bull provided help with data
531 collection. We also thank M.A. McCarthy, J. Stokes and several anonymous reviewers for their
532 valuable comments on earlier versions of this manuscript.

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535
536 **Figure 1.** Location of the study area along the Hume Freeway in south-east Australia (inset).

537 Major towns (black squares) and the position of retrofitted and newly-installed crossing
538 structures (circles) are indicated. At some sites, multiple structures are present as identified in
539 Table 1.



540

541 **Figure 2.** Canopy bridges (top left) and glider poles (top right) along the Hume Freeway in
542 south-east Australia. Monitoring equipment (bottom left and right) included motion-triggered
543 cameras (1), active-infrared sensors (2), PIT tag antennae (3) and power supply (4).

544

545



546

547 **Figure 3.** Video screen-shots of squirrel gliders on the cross-beam of the glider pole at Little
548 Billabong with male head gland (left) and ear notch (right) visible.

549

550 **Table 1.** A description of the crossing structures present at each site. Road width measures the width of the treeless gap created by the road corridor
 551 (trunk to trunk). Squirrel glider activity index refers to average number of individuals per hectare based on concurrent mark-recapture surveys
 552 (described in Appendix 1). Max. glide distance refers to the maximum distance between glider poles and/or roadside trees.

Site	Structures present	Road width (m)	Max. distance to roadside trees (m)	Bridge length (m)	No. of glider poles	Pole heights (m)	Max. glide distance (m)	Squirrel glider activity index	General description
<i>Victoria – retrofitted to existing freeway</i>									
Longwood	Bridge 1	80	9	73	-	-	-	0.33	Above road canopy bridge.
Violet Town	Bridge 2	94	9	86	-	-	-	0.23	Above road canopy bridge.
Balmattum	Pole 1	80	-	-	2	14–16	47	0.34	One pole in centre median, one on roadside.
Baddaginnie	Pole 2	62	-	-	1	16	31	NA	Pole in centre median
Warrenbayne	Pole 3	75	-	-	1	15	39	0.13	Pole in centre median
<i>New South Wales – installed during freeway construction</i>									
Sages	Bridge 3	70	12	63	-	-	-	0.18	Above-road canopy bridge.
	Pole 4	76	-	-	2	15–18	30	“	One pole in centre median, one on roadside.
	Pole 5	88	-	-	2	16–18	35	“	One pole in centre median, one on roadside.
Blue Metal TSR	Bridge 4	75	5	58	-	-	-	0.26	Above-road canopy bridge.
	Pole 6	103	-	-	4	15–17	28	“	Two poles in centre median, two on roadsides.
Yarra Yarra Creek	Bridge 5	151	4	140	-	-	-	1.05	Under-road canopy bridge.
Little Billabong	Pole 7	60	-	-	1	14–18	29	0.10	Pole in centre median.

Site	Structures present	Road width (m)	Max. distance to roadside trees (m)	Bridge length (m)	No. of glider poles	Pole heights (m)	Max. glide distance (m)	Squirrel glider activity index	General description
Westby	Pole 8	66	-	-	3	13-18	26	0.05	One pole in centre median, two on roadsides.
	Pole 9	66	-	-	3	13-18	30	"	One pole in centre median, two on roadsides.
Kyeamba Creek	Pole 10	56	-	-	2	13-18	28	0.59	One pole in centre median, one on roadside.
	Pole 11	68	-	-	2	16	29	"	One pole in centre median, one on roadside.
MR1	Pole 12	69	-	-	1	15-18	38	0.23	Pole in centre median.
Kyeamba TSR	Pole 13	93	-	-	4	15-18	28.5	0.57	Two poles in centre median, three on roadsides.
	Pole 14	382	-	-	5	14-17	184	"	Two poles in centre median, three on roadsides.
	Pole 15	244	-	-	5	15-17	110	"	One pole in centre median, three on roadsides.

554 **Table 2.** Monitoring effort at each site with motion-triggered cameras and PIT tag readers. At
 555 canopy bridges, camera nights shows the number of nights at least one camera was operational,
 556 and PIT reader nights shows the number of nights at least one PIT tag reader was operational.
 557 The number of nights that units at each end of the bridge were simultaneously operating is
 558 given in parentheses. Hyphen indicates no monitoring effort.

Site	Structures present	Camera nights	PIT-tag reader nights
Longwood	Bridge	108 (102)	*151 (0)
Violet Town	Bridge	199 (79)	*99 (0)
Balmattum	Pole	234	-
Baddaginnie	Pole	270	-
Warrenbayne	Pole	107	-
Sages TSR	Bridge	265 (102)	240 (30)
	Pole 1	231	-
	Pole 2	128	-
Blue Metal TSR	Bridge	235 (43)	271 (73)
	Pole	133	-
Yarra Yarra Creek	Bridge	161 (81)	272 (125)
Little Billabong	Pole	258	-
Westby	Pole 1	152	-
	Pole 2	152	-
Kyeamba Creek	Pole 1	75	-
	Pole 2	279	-
MR1	Pole	268	-
Kyeamba TSR	Pole 1	258	-
	Pole 2	268	-
	Pole 13	148	-

559 *PIT tag readers were operational for 6–14 hours per night

563 **Table 4.** Monitoring results from cameras and PIT tag readers at each canopy bridge for each
 564 species, including: the nightly rate (number of crossings per night of operation); the percentage
 565 of crossings that were confirmed by units at each end of the bridge; the average number of
 566 tagged squirrel gliders and common brushtail possums present in the habitat surrounding each
 567 canopy bridge (detail in Appendix 1); and the identity (ID) of individuals detected by the PIT tag
 568 reader (♂=male, ♀=female). *indicates 'visit' only. Hyphen indicates 'not applicable'

Site	Longwood	Violet Town	Sages TSR	Blue Metal TSR	Yarra Yarra Creek
Squirrel glider					
<i>Average MNKTBA</i>	2.3	3.0	4.3	8.3	4.0
<i>Crossings detected by camera</i>					
Total number	453	2	0	0	0
% Confirmed	82%	0%			
Nightly rate	4.19	0.01	-	-	-
<i>Crossings detected by PIT reader</i>					
Total number	244	-	0*	-	-
% confirmed	9%				
Nightly rate	1.62	-	-	-	-
No. indiv.	3	0	1	0	0
ID: nightly rate	♂H1: 0.67 ♀P3: 0.79 ♀Z1: 0.15	-	♀J5: 0*	-	-
Common brushtail possum					
<i>Average MNKTBA</i>	11.7	14.3	1	7.8	4
<i>Crossings detected by camera</i>					
Total number	2	227	0	0	0
% Confirmed	100%	35%	-	-	-
Nightly rate	0.02	1.14	-	-	-
<i>Crossings detected by PIT reader</i>					
Total number	19	120	0	0	0
% Confirmed	5%	27%	-	-	-
Nightly rate	0.13	1.21	-	-	-
No. indiv.	1	4	0	0	0
ID: nightly rate	♀B1: 0.13	♂98: 0.22 ♀92: 0.95 ♂M1: 0.02 ♀Z6: 0.03	-	-	-
Common ringtail possum					
<i>Crossings detected by camera</i>					
Total number	94	270	0	22	0
% Confirmed	85%	26%	-	45%	-
Nightly rate	0.87	1.36	-	0.09	-
Brush-tailed phascogale					
<i>Crossings detected by camera</i>					
Total number	2	0	0	0	0
% Confirmed	0%	-	-	-	-
Nightly rate	0.02	-	-	-	-

569 **Table 5.** Parameter estimates from the Poisson regression of use of glider poles by squirrel
570 gliders. SD is standard deviation.

Parameter	Mean	Standard error	95% credible interval
Grand mean	-3.11	1.45	[-6.23, -0.63]
Effect of number of poles	-1.26	1.33	[-3.92, 1.45]
Effect of gap width	-0.12	0.23	[-0.58, 0.38]
SD Residual error	1.10	0.49	[0.42, 2.35]
SD Structure error	3.89	1.41	[1.97, 7.39]

571

572

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782

783 **Appendix 1 – Mark-recapture surveys at crossing structure sites**

784 We obtained data on the local squirrel glider and common brushtail possum populations using
785 data from a concurrent mark-recapture study. Data were available for 12 of the 13 sites. Each
786 site was surveyed between one and four times between September 2011 and February 2013,
787 with the exception of Baddaginnie, where no surveys were conducted. The trapping surveys
788 covered the majority of the mature woodland within ~600 m of the crossing structure (or
789 crossing zone, where multiple structures were present at a single site) on both sides of the
790 freeway.

791 Wire-cage traps (17 cm x 20 cm x 50cm, Wiretainers Pty Ltd) were baited with a mixture of
792 honey, oats and peanut butter and placed 3–5 m high on tree trunks. The mean number of traps
793 set was 26 (range 8–38) per site per survey depending on the shape and extent of available
794 habitat surrounding the crossing structure. Traps were spaced at 50–100 m intervals and
795 arranged in a grid or transect extending up to 600 m away from the crossing structure. Traps
796 were set for an average of six nights per survey (range 4–8). The trap effort at each site varied
797 from 125–635 nights (mean 406).

798 Traps were checked each morning and all animals were weighed and their tooth-wear, gender
799 and reproductive status recorded. Animals were marked with a unique tattoo in the ear flap and
800 two 2 mm tissue biopsies were taken from the ear margin for use in genetic analysis for another
801 study. Each squirrel glider and common brushtail possum captured was implanted with a PIT
802 tag under the skin between the shoulder blades (ID 100, Trovan, Microchips Australia Pty Ltd).
803 We did not implant PIT tags in other species during these surveys (e.g. common ringtail
804 possums) because they are rarely detected in surveys using wire-cage traps.

805 Mark-recapture detected 267 animals during 4,883 trap nights. Species detected included
806 squirrel gliders ($n=88$), common brushtail possums ($n=147$), common ringtail possums ($n=1$),
807 sugar gliders ($n=12$), brush-tailed phascogales ($n=3$) and yellow-footed antechinus ($n=16$). We
808 calculated the Minimum Number of Animals Known To Be Alive (MNKTBA) for squirrel gliders
809 at each site and for common brushtail possums at canopy bridge sites. Where multiple surveys
810 were conducted, we used the average MNKTBA across all surveys at that site (Table A1). This
811 information was used to calculate the activity index for squirrel gliders presented in Table 1 of
812 the main text. The activity index was determined by dividing the average MNKTBA by the area
813 of habitat trapped at each site. The area of habitat trapped (in hectares) was calculated as the
814 area in which traps were set plus a buffer zone of 50 m to include any habitat immediately
815 adjacent to the trapping area (Table A1). The average MNKTBA for both squirrel gliders and
816 common brushtail possums at canopy bridge sites was used to compare the number of

817 individuals present at each site (i.e. the number of animals likely to have access to the canopy
 818 bridge at any one time) with the number that were detected crossing the canopy bridge by the
 819 PIT tag reader. This data is presented in Table 4 of the main text.

820 **Table A1.** Mark-recapture trapping effort at each site. The average MNKTBA for squirrel gliders
 821 and common brushtail possums is shown (+/- 1 SE in parentheses).

Site	Trapping area (ha.)	Number of surveys	Total number of trap nights	Squirrel glider activity index (indiv./ha.)	Average MNKTBA	
					Squirrel gliders	Common brushtail possums
Longwood	6.9	3	532	0.33	2.3 (0.3)	11.7 (2.0)
Violet Town	10.3	4	460	0.23	2.3 (0.5)	10.8 (1.0)
Balmattum	10.4	2	125	0.34	3.5 (1.5)	-
Warrenbayne	15.7	1	140	0.13	2 (NA)	-
Sages TSR	23.4	3	575	0.18	4.3 (0.7)	1 (0.4)
Blue Metal TSR	32.3	3	633	0.26	8.3 (0.3)	7.7 (0.9)
Yarra Yarra Creek	3.8	3	166	1.05	4.0 (0.6)	0.3 (0.3)
Little Billabong	19.1	3	456	0.10	2 (0.6)	-
Westby Lane	19.2	3	517	0.05	1 (0.6)	-
Kyeamba Creek	9.6	3	439	0.59	5.7 (0.7)	-
MR1	8.8	3	205	0.23	2 (0.6)	-
Kyeamba TSR	18.3	3	635	0.57	5 (0.6)	-

822

823

824 **Appendix 2 - Model code**

```

825
826 model{
827   for (i in 1:Nobs) {
828     x[i] ~ dpois(lambda[i])
829     lambda[i] <- theta[i] * t[i]
830     theta[i] <- exp(mu[i])
831     mu[i] ~ dnorm(phi[i], prec[1])
832
833     phi[i] <- max(min(GM + npoles.eff * (npoles[i] - 2) + gap.eff * (gap[i] - 30) + str.eff[str[i]],99),-
834 99)
835   }
836
837   for (k in 1:Nstr) { str.eff[k] ~ dnorm (0, prec[2]) }
838
839   GM ~ dnorm(0,0.0001)
840   npoles.eff ~ dnorm(0,0.0001)
841   gap.eff ~ dnorm(0,0.0001)
842
843   for (m in 1:2) {
844     prec[m] <- 1/sd[m]/sd[m]
845     sd[m] ~ dt(0, .0016, 1)T(0,)
846   }
847
848   pred.mean.rate <- exp(GM)
849
850 }
851
852 }
853 END MODEL
854
855 DATA
856 list(Nobs=26, Nstr=13)
857 t[] x[] str[] npoles[] gap[]
858 228 3 1 2 47
859 6 1 1 2 47
860 30 36 2 1 39
861 77 124 2 1 39
862 206 7 3 1 31
863 59 10 3 1 31
864 5 1 3 1 31
865 217 246 4 2 30
866 14 23 4 2 30
867 114 2 5 2 35
868 114 0 5 2 35
869 119 4 6 4 28
870 14 6 6 4 28
871 258 224 7 2 29
872 138 0 8 3 26
873 14 0 8 3 26
874 138 0 9 3 30
875 14 0 9 3 30
876 61 118 10 2 28
877 14 26 10 2 28

```

878 279 10 11 2 29
879 60 0 12 1 38
880 208 0 12 1 38
881 70 0 13 4 28.5
882 20 1 13 4 28.5
883 168 0 13 4 28.5
884 END
885