Effectiveness and efficiency of temporary fences as mitigation measures for preventing amphibians roadkill

†LE BRISHOUAL Meven[1,2], TANVIER Clara[2], DEHAUT Nathan[2,3], MIAUD Claude[1], JUMEAU Jonathan[2]

1 : CEFE, Univ Montpellier, CNRS, EPHE-PSL University, IRD, 34293 Montpellier, France

2 : Collectivité européenne d'Alsace, CERISE, Place du Quartier Blanc, 67964 Strasbourg, Cedex 9, France

3 : Centre d'Études Biologiques de Chizé, 405 route de Prissé la Charrière, 79360 Villiers-en-Bois, France

†Corresponding author: mevenlebrishoual@gmail.com

ABSTRACT

1- Temporary fences are used to prevent amphibians from accessing dangerous areas. These fences can be built out of different materials and field studies have shown that some of them still allow for trespassing.

2- In this study we compared, in controlled conditions and using experimental arenas, the effectiveness and efficiency of the three most commonly used materials for temporary amphibian fences (polyethylene tarp, polyethylene netting, and wire meshing) and of the presence of an overhang, on two amphibian species with distinct modes of locomotion (walker/short-distance jumper; long-distance jumper). The polyethylene tarp fence, and fences equipped with an overhang, were the only designs able to stop every individuals for three consecutive trials.

3- Fences that were not slick or equipped with an overhang could be crossed at any height by both species.

4- For non-climbable fences, long-distance jumper species required a 60 cm high fence to be stopped while the walker/short-distance jumper species only required 20 cm.

5- The walker/short-distance jumper individuals interacted 1.7 times more with the polyethylene netting and wire meshing than the polyethylene tarp, due to either differences in opacity between materials or the impossibility to climb on the tarp. The long-distance jumper species was not deterred by the tarp fence and interacted equally with all materials.

6- When considering price, durability and ease of use while maintaining effectiveness, the polyethylene netting fences equipped with an overhang were the most efficient option for long-term use.

7- **Synthesis and applications:** amphibian fences should systematically be equipped with a 10 cm overhang at their top to ensure their effectiveness. Polyethylene tarp is the best option for short-term use while polyethylene netting is the best option for long-term use.

Keywords: amphibians; *Bufo bufo*; locomotion; *Rana dalmatina*; road ecology; roadkill mitigation; wildlife fence

INTRODUCTION

The life cycle of most amphibians requires them to cross roads separating terrestrial habitats and breeding aquatic habitats (Joly 2019, Cayuela et al. 2020). Amphibians are vulnerable to traffic because they move slowly and can display a freezing behaviour in the face of danger (Carr and Fahrig 2001, Hels and Buchwald 2001, Gibbs and Shriver 2005, Mazerolle et al. 2005). Many species also exhibit temporally concentrated migrations, during which thousands of individuals may simultaneously cross roads and suffer high mortality rates, even under low traffic conditions (Gibbs and Shriver 2005, Orłowski et al. 2008, Helldin and Petrovan 2019). Road mortality surveys which account for amphibians place them as the group with the highest mortality counts or rates, to a point that may lead to

population decline (Smith and Dodd 2003, Gibbs and Shriver 2005, Glista et al. 2008, Jochimsen et al. 2013, Beaune 2019).

In order to reduce amphibian roadkill, mitigation measures have been implemented along roadsides known to be mortality hotspots (Puky 2003). These measures include traffic and speed reduction, road closures, translocation of breeding habitat, or limiting road access with fences (Puky 2003, Schmidt and Zumbach 2008, Beebee 2013, Jochimsen et al. 2013). The latter prevents amphibians from getting on the asphalt while guiding them towards underpasses or pitfall traps (Schmidt and Zumbach 2008, Beebee 2013). Fences can be permanent or temporary. Permanent fences vary in material with wire netting, polyethylene netting, concrete or metal often being used, with recommended heights between 45 and 60 cm (Conan 2023, Gould et al. 2024). The main caveat of permanent fences is their high cost and need for vegetation maintenance (Schmidt & Zumbach 2008). Temporary fences are the most frequently used, representing 84% of roadside installations in France (Eggert 2019), and also being used as exclusion fences for construction sites. They are usually installed during the activity period of amphibians, or construction duration only, and their fences mostly consist of polyethylene netting, wire netting, or opaque polyethylene tarp (Arntzen et al. 1995, Iuell et al. 2003, Morand 2019). Permanent fences are associated with underpasses allowing migrating amphibian to cross the roads. On contrary, temporary fences usually need to be associated with pitfall traps, requiring the daily intervention of operators to manually transfer amphibians across the road (Puky 2003, Schmidt and Zumbach 2008, Morand 2019, Isambert and Didier 2024).

Even though temporary fences are effective at reducing roadkill, they do not always prevent individuals from reaching the road (Smith and Sutherland 2014, Gould et al. 2024). Beaune (2019) observed that over 10% of contacted migrating amphibians were roadkills despite the installation of a temporary fence, a rate incompatible with the persistence of small populations (Gibbs and Shriver 2005, Beaune 2019). The individuals can bypass the fence, or climbed over it. The former behaviour has been witnessed and is known to generate excess mortality at fences extremities (Huijser et al. 2016, Helldin

and Petrovan 2019). It can be dealt with by curving the fence in a U-turn (Brehme et al. 2021) or by placing a pitfall trap or a tunnel at each extremity of the fence (Helldin and Petrovan 2019). Mortality linked to individuals climbing over the fence would indicate an improper fence design that should be improved, but knowledge is lacking on this subject. Temporary fence design and materials vary greatly between installations. Wire netting (meshing size 6.5 x 6.5 mm) and polyethylene netting fences are commonly used but amphibians can climb over them in the absence of a sufficiently large overhang (Arntzen et al. 1995, Conan et al. 2022, Gould et al. 2024) . Polyethylene tarp fences have been shown to be effective at reducing trespass rates (Woltz et al. 2008) but was not tested in comparison with other materials. To our knowledge, other temporary fence studies are only descriptive, and have not tested the fences effectiveness in controlled conditions (Ganet and Vacher 2012, Gould et al. 2024).

The lack of comparative information about temporary fence materials and designs prevents their optimisation while effective designs are strongly needed as amphibian populations continue to decline in Europe (Helldin and Petrovan 2019, Chanson et al. 2023). This study thus focused on comparing commonly used temporary fences (wire meshing, polyethylene netting and polyethylene tarp) in controlled conditions. Our aim was (1) to determine the most effective material, height, and installation of fences to prevent amphibians crossing. We expected differences related to species jumping and climbing abilities, with tall and smooth materials being the most effective; and (2) to find the most efficient temporary fence in order to make recommendations tailored to the capabilities of the various stakeholders.

MATERIALS & METHODS

Model species

Two amphibian species with contrasted adult modes of locomotion were used. The Common toad (*Bufo bufo* Linnaeus, 1758) represented species moving by walking, hopping. It has a stout body with

short hind limbs, individuals can grow up to 11 - 18 cm depending on the latitude (Speybroeck et al. 2018). The Agile frog (*Rana dalmatina* Fitzinger in Bonaparte, 1839) represented species mainly moving by jumping. It has a smaller frame, long hind limbs and can grow up to 8 cm (Speybroeck et al. 2018). Both species are known to climb on fences. The maximum jumping distance of toads of the genus *Bufo* has been measured in the 10-30 cm range while species of the genus *Rana* were in the 30-200 cm range (Emerson 1978, Zug 1985, Speybroeck 2018).

Forty individuals of each species were captured during their migration season (February 25th 2025 for the common toads and March 22nd 2025 for the agile frogs) and tagged using an RFID PIT. For each species, 30 individuals came from a site equipped with temporary fences (wire meshing) and 10 from a site without fences (designated as 'naïve') in order to control for a potential effect of learning and memory on crossing performances. Ten individuals were used per condition to allow the use of linear models while limiting our impact on wild population as much as possible. Every individual was weighted and measured (SVL: from the snout to the end of the ischium) on capture using an electronic scale (Aroma-zone, ± 0.01 g) and an electronic calliper (0-150 mm, accuracy: ± 0.03 mm, Tesa technology®, Renens, Switzerland). Capture and housing conditions are detailed in **Sup. 1**). Captures were authorised under the decree AP N° 2024-DREAL-EBP-0054, delivered by the French DREAL Grand Est. The implantation protocol used during this study was validated by the ethics committee for animal experimentation n°036 (CE036; #53332 – 2025012917445217 v 3).

Experimental setup

All tests were conducted inside a 2000 m^2 fenced semi-natural outdoor enclosure located between two motorways, Duttlenheim, France (48.512594 °N, 7.582062 °W) in four arenas built out of wood (1*0.5*1 m, length*width*height; **Fig. 1**). The arenas were placed on bricks and underneath a polyethylene tarp to keep them out of the rain and isolate them from the ground. Arenas consisted of two compartments: (A) 'departure' (25x50 cm) which consisted of a movable wooden platform (unattractive) that allowed to test multiple fences height, while the (B) 'arrival' compartment (75x50

121 cm) was enriched with moist soil, moss and hides made of branches. Behind the rear side of the 'arrival'
122 compartment, a speaker (Pulsar® 2 × 3 W speaker, Enkhuizen, Netherlands) played mating calls from *B.*
123 *bufo* and *R. dalmatina* to motivate amphibians to cross the fence during the trials as male calls
124 (conspecific or not) are known to attract resident amphibian species (Muller & Schwarzkopf 2017,
125 Testud et al. 2020). The top and the front of the arena were closed with plexiglass, with thin openings
126 on the top to allow for ventilation. The two compartments were separated by a fence. The fence
127 material differed between arenas, with three different materials used: (1) polyethylene tarp (T), (2)
128 polyethylene netting (N), and (3) 6.5 mm wire meshing (W, **Fig. 2**). Wire meshing fences were used in
129 two arenas: one for the group ''wire meshing'' (W), and one for the group 'naive' (Wn) other materials
130 could not be tested for experience because they were not commonly used in the field. Each fence was
131 equipped with a 10 cm horizontal movable overhang to test the impact of the overhang compared to a
132 straight fence. Its dimensions were chosen according to results of previous studies, in which a 10 cm
133 overhang was sufficient to prevent the crossing of most amphibian species (Conan et al. 2022, 2023).
134 The platform of the departure compartment was mounted onto wooden blocks (height = 10 cm) in
135 order to make the fence height vary from 20 to 60 cm with a 10 cm increment.

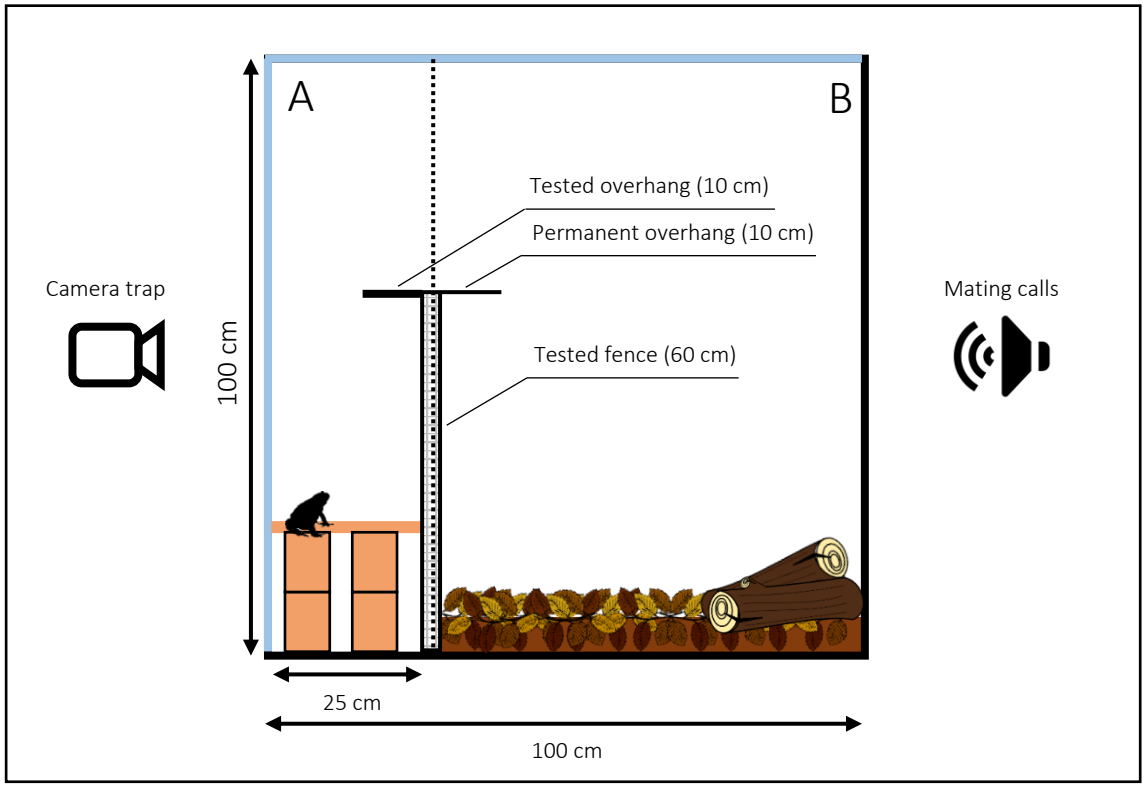


Figure 1: Side view of the experimental arenas. A, the departure compartment composed of a movable wooden floor placed on 10 cm wooden blocks to set up the fence height. B, the arrival compartment composed of moist forest floor and shelters. The tested overhang could be folded back in order to test the condition or not, a permanent overhang prevented individuals from crossing back into the departure compartment. The black sides of the box represent wooden panels; the light blue sides represent plexiglass panels. The Departure compartment was photographed every five min by a camera trap; mating calls were played from behind the Arrival compartment to attract amphibians.

Figure 2: Tested fence materials. I) the polyethylene tarp (T), II) the polyethylene netting (N), and III) the wire meshing (W, Wn). The overhang was set up to be tested in I and II and folded back in III.

Experimental trials

In order to test the three fence materials (polyethylene tarp T, polyethylene netting N, and wire meshing W) and the experience of the amphibians under the W material (naïve Wn or experienced W), the 40 individuals of both species were separated into four groups of 10 individuals. There was one group per fence material (T; N; W) and one for the naive individuals (Wn). The denomination of ''group''

(*i.e.* ''tarp group'') refer hereafter exclusively to the tested individuals, while the denomination of ''fence'' (*i.e.* ''tarp fence'') refer to the physical object. Before starting the trials, each group had one habituation night during which they could explore the arena without any fence. Given the nocturnal activity of the tested species, all experiments were conducted at night between February 26th 2025 and April 11th 2025, and only on nights for which the minimum forecasted temperature was at least 5°C. At the beginning of a trial, all 10 individuals of each group were placed into the 'departure' compartment of their arena and had until the following morning to cross the fence. Trials lasted for 12 to 17 hours, usually between 06:00 PM and 09:00 AM. During the entire trial duration, photos were taken every five min using camera traps (Cuddeback X-Change™ Color - Model 1279). Camera traps were placed one meter in front of the arena to record amphibian behaviour and interactions with the fence during the night. The following morning, individuals were removed from the arenas and were identified (PIT tags) to determine their crossing status (blocked = 1 /passed = 0). They were then transferred back to their holding tanks. If the fence managed to block every individual at a given height, this height was tested up to two additional consecutive nights, after which it was considered effective and designated H_{eff} for "effective fence height". We tested five fences heights (20, 30, 40, 50 and 60 cm). The 10 cm height was excluded as it was shown to be ineffective for similar species in Conan *et al.*, (2023). Testing for each group stopped after the effective fence height (H_{eff}) was found, or if at least one individual managed to cross the tested fence at 60 cm, in which case we considered the fence ineffective. In order to reduce the time needed to identify H_{eff}, toads were tested starting at 20 cm, with the height progressively increasing, as we expected them to be stopped by lower fence heights. In contrast, frogs were tested starting at 60 cm and going down since they were expected to be able to cross at least 40 cm (Conan et al. 2022, 2023). This procedure was repeated for both overhang conditions (with and without). Night temperatures at the nearby weather station of Holtzheim (~5 km) were downloaded from the opendatasoft.com website.

Analyses & statistics

A scan sampling method (Altmann 1974) was used to analyse the behaviour of the individuals with a five minutes time step, corresponding to the delay between each photo (ethogram in **Table 1**). Since individuals could not be identified in the photos, the sampling occurred at the group scale with up to 10 behaviours recorded per scan depending on the number of individuals still present in the departure compartment. For each group, the number of interactions with the fence per night was calculated. For each night and group, the interactions with the fence was recalculated for each hour as the proportion of the Interaction behaviour in overall activity (Overall activity = Interaction + Other activity, **Table 1**).

Table 1: Ethogram for the scan sampling behavioural analyses.

Behaviour	Description
Interaction	The individual has at least one limb grabbing or pushing up against the fence
Other activity	The individual is active without interacting with the fence
Resting	The individual is lying on the ground or on a conspecific
Out of sight	The individual is not visible

Effectiveness

For each species, the effect of the group (T, N, W, Wn), height (20, 30, 40, 50 and 60 cm), and the overhang (with, without) was tested on the individual crossing status using ANOVAs based on binomial generalised linear models (**Sup. 2** for model type and parametrisation). The effects of the mean night-time air temperature, individual SVL, date, and the number of interactions with the fence were included in the model as fixed control variables to ensure that any of the observed effect could be attributed to the fence rather than these covariates (Bennett 1984, Swoap et al. 1993, Navas et al. 1999, Oromí et al. 2010, Moreno-Rueda et al. 2020, Conan et al. 2023). The models being binomial, they estimated the probability of the fence blocking the amphibians, which we used to describe fence effectiveness. The ''overhang present'' modality and the tarp (T) modality of the group variable were excluded from the statistical analyses for the common toads since these conditions always blocked the

individuals, and we considered them significantly different from the other conditions. Effective fence height (H_{eff}) was also compared between groups (T, N, W, Wn) with no statistical analyses.

Efficiency

We defined efficiency in two ways. Firstly, as the interactions with the fence. Fences with which amphibians interacted less were considered more efficient since they would prevent exhaustion. To assess this we tested the effect of group (T, N, W, Wn), height, the presence of the overhang, and time elapsed since the beginning of the trial on the interaction with the fence using ANOVAs based on beta zero-inflated generalised linear mixed models (**Sup. 2**). Mean night temperature was used as a control variable and date was included as a random effect.

Secondly, we explored the cost-benefits balance of each fence concerning its deployment in the field. The following criteria were assessed: cost per 100 meters of fence, mechanical durability, reparability, complexity of installation, and handleability. Cost was the mean price for new fences of each material gathered from readily available online amphibian fences (i.e., fences for which the suppliers provided the information online without needing a quote) and local operators feedback. Lifespan was either the lifespan or UV resistance lifespan advertised by the manufacturer or the replacement rate used by local operators for the material. Mechanical durability, reparability, installation complexity, and handleability were compared based on the feedback of local operators. Prices and currency conversion rates of December 2025 were used (**Sup. 4**).

Analysis and graphs were performed using R software® (R Core Team 2025; v 2024. 12.1+563; packages: stats, lme4, glmTMB, DHARMa, nlme, ggplot2, MASS, MuMIn, emmeans, car) with significant threshold set to $p < 0.05$. Models underwent variable selection through model averaging (**Sup. 3**) and Tuckey HSD post-hoc tests were used when needed. Behavioural sampling was realised with the BORIS® software (v 9.4.1; Friard & Gamba, 2016).

RESULTS

A total of 27 nights of trials were conducted: 10 nights for toads and 17 nights for frogs. 13 145 single behavioural events were recorded for the Common toad and 15 675 for the Agile frog. Common toads produced a mean of 789.64 ± 78.31 active behaviours (interaction + other activity, **Table. 1**) per night and 59.01 ± 2.53 active behaviours per hour (respectively, 79.00 ± 7.83 and 5.90 ± 0.25 per individual). Agile frogs produced a mean of 571.71 ± 22.48 active behaviours per night and 47.64 ± 2.24 active behaviours per hour (respectively, 57.17 ± 2.25 and 4.76 ± 0.22 per individual). Towards the end of the trials of the agile frogs, two individuals from the tarp group died and one was lost. The first individual that died was found with a flank injury (PIT tag implantation wound re-opened) one morning and did not survive the day despite treatment, it could not partake the last five trials. The second was found dead in the arrival compartment seemingly desiccated despite normal conditions in the arena, its body weight was not abnormal before the trial. It could not attend the last four trials. Finally, the lost individual could not be found before starting the penultimate trial, its fate is unknown but it most likely escaped back to the wild since we could not find it in the facilities.

Effectiveness

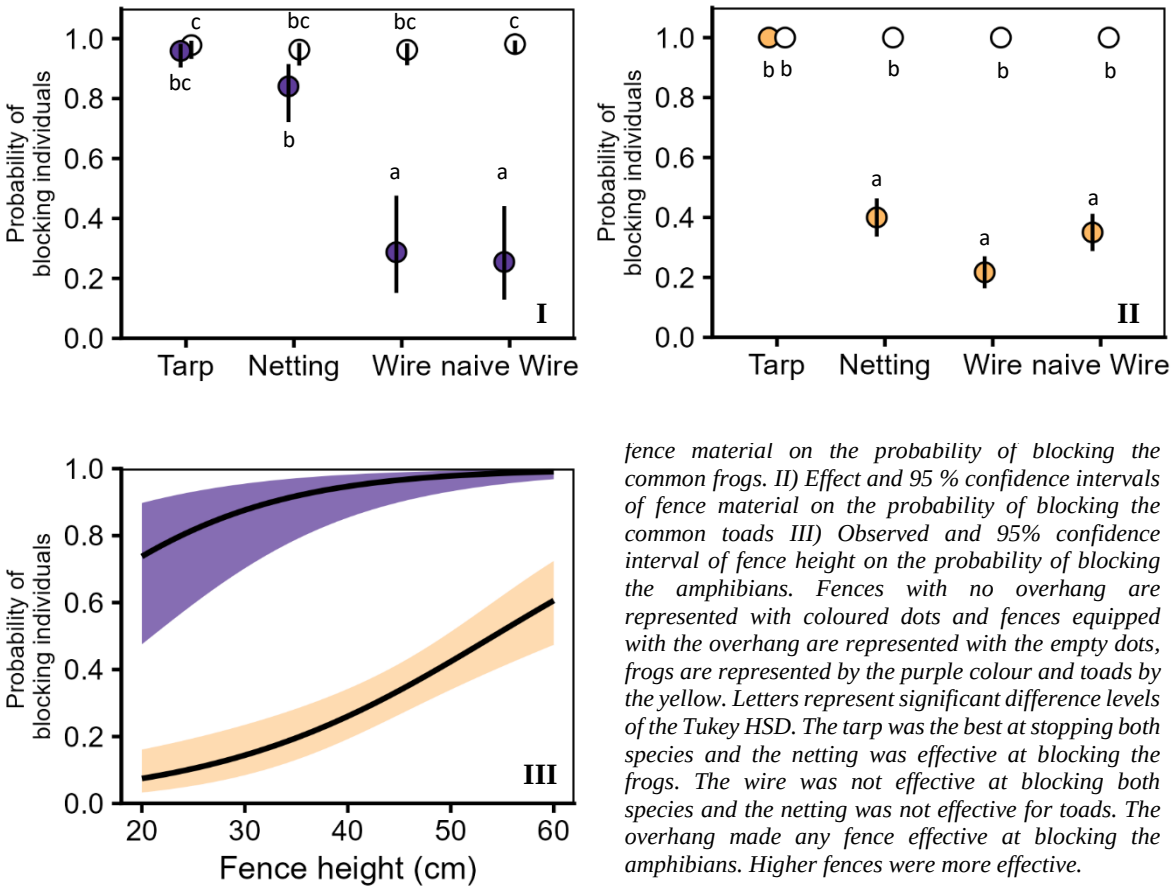
The individual SVL, mean night air temperature, date, and number of interactions with the fence had no effect on the probability of the fence blocking the amphibians as they were always discarded during model averaging (**Sup. 3**).

Probability of blocking the amphibians

When the overhang was present, every fence had a similarly high probability of blocking the amphibians, with probabilities ranging from 0.96 [0.91 – 0.98] (polyethylene netting, N) to 0.98 [0.95 – 0.99] (naive wire, Wn) for frogs, and no recorded crossings for toads (**Fig. 3 I, II**).

When no overhang was present, only the tarp fence (T) retained its effectiveness while polyethylene netting (N) and wire netting fences (W and Wn) showed a degraded performance at

blocking the amphibians of both species (Frogs: $\chi^2 = 97.49$, df = 3, $p < 0.01$; Toads: individuals could now cross the fence, (**Fig. 3 I, II**). For frogs the degradation in performance was 12.91 % for polyethylene netting fences (N), and 69.70 % and 73.61 % for the wire meshing fences (W and Wn) (**Fig. 3 I**). For toads, the degradation in performance was 60.00 % for polyethylene netting fences (N), and 78.30 % and 65.00 % for wire meshing fences (W and Wn) (**Fig**. 3 II). Experience had no effect on the probability of the fence blocking the amphibians as the naive (Wn) and non-naive wire (W) groups performed equally for both species (**Fig. 3 I, II**).



fence material on the probability of blocking the common frogs. II) Effect and 95 % confidence intervals of fence material on the probability of blocking the common toads III) Observed and 95% confidence interval of fence height on the probability of blocking the amphibians. Fences with no overhang are represented with coloured dots and fences equipped with the overhang are represented with the empty dots, frogs are represented by the purple colour and toads by the yellow. Letters represent significant difference levels of the Tukey HSD. The tarp was the best at stopping both species and the netting was effective at blocking the frogs. The wire was not effective at blocking both species and the netting was not effective for toads. The overhang made any fence effective at blocking the amphibians. Higher fences were more effective.

Fence height only had an effect on toads for netting (N) and wire (W, Wn) fences not equipped with an overhang since the other conditions always stopped them. For those, higher fences were more performant at blocking the toads (slope = 0.07, se = 0.02, z = 4.72, $p < 0.01$), although the probability of blocking the individuals was moderate at best (60 cm: 0.61 [0.47 – 0.72], **Fig. 3 III**). For Agile frogs, the effect of fence height did not differ between materials or according to the presence of an overhang

since the interaction of these variables was discarded during model selection. Higher fences were also more performant (slope = 0.09, se = 0.01, z = 7.62, p < 0.01). For this species however, the probability of blocking the individuals was already 0.74 [0.48 - 0.89] at 20 cm, 0.95 [0.86 – 0.98] at 41 cm, and 0.99 [0.97 – 1.00] at 60 cm (**Fig. 3 III**).

Minimum effective height

For toads, fences could either be climbed over and be crossed at any height, or be impossible to climb and be effective at 20 cm (**Table 2**). For the agile frogs, fences could either be climbed over and be crossed at any height, or be impossible to climb and need to be 60 cm high to prevent the frogs from jumping over them (**Table 2**).

Table 2: Minimum effective fence height of each fence material, with and without an overhang, for the Common toad and the Agile frog.

Fence material	Overhang	Minimum effective height	
		Common toad	Agile frog
Polyethylene tarp	No	20 cm	60 cm
Polyethylene tarp	Yes	20 cm	60 cm
Polyethylene netting	No	ineffective	ineffective
Polyethylene netting	Yes	20 cm	60 cm
Wire meshing	No	ineffective	ineffective
Wire meshing	Yes	20 cm	60 cm

Efficiency

There was no effect of the mean air night temperature, the fence height, and the presence of the overhang on the proportion of interactions with the fence in overall activity for both species as these variables were discarded during model averaging (**Sup. 3**). In addition, time elapsed since the beginning of the trial also had no effect for the common toads, and the group (T, N, W, Wn) had no effect for the frogs as they were also discarded during model averaging (**Sup. 3**).

Proportion of interaction with the fence

Common toad individuals tested with the tarp fence interacted with the fence 1.7 times less than the other groups (**Fig. 4 I;** $\chi^2 = 30.39$, df = 3, $p < 0.01$). Agile frog interactions with the fence decreased over time (slope = - 0.12, se = 0.02, $p < 0.01$, **Fig. 4 II**). Experience had no effect on the interactions with the fence since there was no difference between the naive (Wn) and non-naive wire (W) groups for the common toads(**Fig. 4 I**), and the group variable was discarded during model selection for the agile frogs.

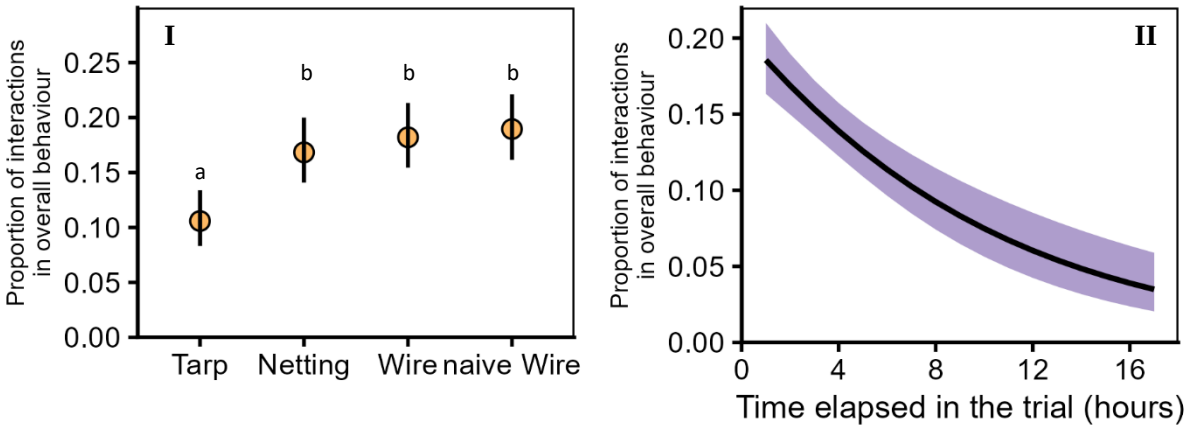


Figure 4: Predicted effect and 95 % confidence intervals of I) fence material and II) time elapsed since the beginning of the trial on the proportion of interaction with the fence in global activity. Common toads are in yellow and agile frogs in purple. Toads interacted less with the tarp fence but kept interacting equally during the night while frogs interacted less with the fence as time passed regardless of the fence material.

Cost-benefits

Fourteen references from 10 manufacturers were gathered from online searches for readily available prices combined with a quote for material used by a local operator (**Sup. 4**). The polyethylene netting fences were the most cost-efficient option (**Table 3**). They had the cheapest cost per 100 m per year of lifespan at 54.17 € ± 11.51 and were the easiest to handle as they were light, resistant enough to be manipulated with no extra care, and could not hurt operators. They were technically less resistant than wire meshing fences but both could be damaged by wild boars leading to a similar functional durability. The tarp fence was quickly and easily repaired as it only needed heavy-duty duct tape to be put back together. The other materials were repaired by sewing the netting or the wires back together,

which was a longer task to perform. The polyethylene tarp fence was however the most complex one to set up, requiring bent poles, guiding threads for the overhang, and tension threads to keep the fence upright. The easiest fence to set up was the wire meshing fence which only needed straight poles and a manual bending of its top to create the overhang. The lack of a guiding structure however meant that the overhang could be improperly formed, rendering it ineffective. Eight local operators gave us feedback after having tried installing polyethylene netting instead of their usual wire fences. Two feedbacks were positive, three neutral, and three negative. Positive feedbacks were an easier and faster installation of the polyethylene netting. The negative feedbacks concerned the increased complexity of the netting fence and that it was harder to set up in sandy grounds.

Table 3: Cost/benefits analysis of the three studied fence types.

	Polyethylene tarp	Polyethylene netting	Wire meshing
Cost (€/100 m)	116.71 ± 10.28	325.49 ± 69.10	1069.06 ± 55.99
Lifespan (years)	2 (UV lifespan)	6 (UV lifespan)	10 (replacement rate)
Cost/year (€/100m)	58.35 ± 5.14	54.25 ± 11.52	89.58 ± 17.86
Mechanical durability	Puncture/tears by mesomammals, blown off by wind/semitrailers	Puncture/tears by macromammals	Puncture/tears by macromammals
Reparability	Duct tape	Sewing (polyethylene thread)	Sewing (steel wire)
Installation complexity	Curved poles, guiding thread	Curved poles, guiding/ tension threads	Straight poles, fence bent to form the overhang
Handleability	Risk of puncture	No drawback	Heavier, wire can cause hand injuries

DISCUSSION

Feedback on experimental design

We tried to reproduce realistic conditions during the trials by placing the arenas outdoors, close to noisy area (motorway), as temporary fences are usually installed next to roads or around construction sites. We also tried to maximize the motivation of the individuals by placing them at night, during the migration season, on a non-attractive substrate after having allowed them to learn the existence of a suitable substrate before the trials (Dall'antonia and Sinsch 2001). We were able to control the crossing success and activity properly by accounting for the effect of temperature, one of the most important drivers of ectotherm activity (Navas et al. 1999, Arnfield et al. 2012, Gunderson and Leal 2015). Two technical points are to be taken in account for the arenas to function properly in the setup we used. The wooden floor of the ''departure compartment'' should be tightly fitting with the walls of the arena and the fence on all four sides, otherwise amphibians will manage to slip under the floor and not complete the trial. Duct taping any gap left after setting up the arena is an easy way to make the wooden floor frog-proof. The second point of attention is condensation: the plexiglass will rapidly be covered with fog if the arena is not well ventilated, obscuring the individuals from the camera traps. It can be solved by drilling small holes in the roof of the arena or by integrating mesh in it

Effectiveness

Walker and jumper species

Our results on the toads were very clear-cut and suggest that overhangs and slick materials like the tarp cannot be crossed by climbing them, at least without the help of an adherence mechanism. We expect them to be effective for any walker/short-distance jumper species in general. A fence presenting toe-holds and no overhang however could be crossed by climbing regardless of its height. Agile frogs were also able to cross 60 cm netting and wire fences without overhangs, however for conditions that were impossible to climb (tarp fence and overhang present), the highest fences they could cross were

50 cm tall. The frogs could only have crossed these fences by jumping over them, setting the maximum vertical jumping performance of the Agile frog between 50 and 60 cm in our experimental setup. This height is lower than what was recorded for *Lithobates pipiens* (Schreber, 1782), another long-distance jumper for which one single individual managed to clear a 90 cm fence, although over 95 % of its conspecifics were blocked at 60 cm (Woltz *et al.* 2008). In order for fences to be effective for long-distance jumpers, they should be both impossible to climb and their height adapted to the most agile species present in the area of deployment. From our findings and the available literature, 60 cm high fences seem to be a minimum to ensure over 95 % of effectiveness for long-distance jumpers.

Adherence climber species

Adherence climbers were initially supposed to be included in this study with the Palmate newt (*Lissotriton helveticus* Razoumovsky, 1789) but an unusually low numbers of migrating individuals prevented us from capturing enough of them to include in our protocol. Even though testing them would have provided more accurate data about temporary fences, we can infer from previous studies how the tested fences could have performed for adherence climbers. Concerning slick surfaces, adult newts were shown to be unable to cross a 35 cm aluminium flashing fence with no overhang (Dodd 1991) while juveniles could not climb higher than 21 cm on wet concrete and never climbed dry concrete (Conan *et al.* 2023). Adult *Lissotriton sp.* have however been reported to climb wet slick plastic tarps successfully (Morand 2019). Newts (*L. helveticus* and *Triturus marmoratus* Latreille 1800) have also exhibited unexpectedly high performance in climbing vertical surfaces like tree trunks and branches (Boissinot *et al.* 2023, Csutoros 2025). This suggests that despite adult newts not being able to cross permanent fence designs, they might be able to climb all three materials tested in our study as long as no overhang is present and if the fences are wet. Adhesive toe pads are a common trait in frogs morphology (Barnes et al. 2011) making tree frog species proficient climbers on almost any surface (Hertwig and Sinsch 1995, Federle et al. 2006, Crawford et al. 2016, Langowski et al. 2018).. They have been shown to easily cross concrete, metal sheets, and polyethylene netting fences up to 120 cm when no overhang was present (Dodd 1991, Conan *et al. 2023,* Gould *et al*. 2024). Tree frogs are unable to

340 overcome 90° 10 cm overhangs but could jump up to 35 cm high (Conan *et al.* 2023, Gould *et al.* 2024).
341 We would expect tree frogs to easily climb any material, and only be stopped by a fence equipped with
342 an overhang, and which would be too high for them to jump over.

343 *Most effective design*

344 Accounting for these considerations, the most effective fence material for amphibians would
345 be the polyethylene tarp as it was the only one able to prevent crossings without an overhang. Materials
346 presenting toeholds can still make effective amphibians fences on the condition that a 10 cm overhang
347 is present at the top of the fence, the addition of an overhang being mandatory regardless of materials
348 if adherence climbers are present or suspected on site. Regardless of the material used, fence height
349 should be at least 60 cm to ensure high effectiveness for long-distance jumper species and should never
350 be less than 40 cm since it already insured a 0.95 probability of blocking such species.

351 Efficiency

352 The tarp was the most effective material, but our results show that the type of material used
353 for the fence is not critical as long as a 10 cm overhang is present, which we strongly advise for in any
354 cases since it always improves the effectiveness of the fence. The addition of an overhang allows to shift
355 the focus of the choice of material from fence effectiveness to efficiency and cost-benefits, a core part
356 of mitigation fences design (Huijser et al. 2009, 2022).

357 *Wire meshing*

358 From our results, the wire meshing fences are the least efficient of the three type of fences. Not
359 only is their cost per year twice as much has the other two materials but smaller newts (*Lissotriton sp.*)
360 can get stuck in the meshing or crawl through it (Association Les Piverts 2024, and our personal
361 observations). The mean skull width of adult *Lissotriton helveticus* (~7 mm; Bettencourt-Amarante et
362 al., 2024) is smaller than the diagonal of a 6.50 mm square (9.19 mm), the commonly used mesh size in
363 France (Morand 2019, Conan et al. 2022), which allows newts to pass their heads through it. A mesh

size of 3 mm (4.24 mm diagonal) should prevent this. The advantages of wire meshing do not counterbalance its cost since it can still be damaged by wildlife and might require maintenance during the migration period, and the overhang folding can be done incorrectly on large portions of fence (Jumeau 2017).

Polyethylene tarp

The two polyethylene materials were similar in term of cost/durability. The tarp was more fragile as it could be easily punctures and blown off by wind gusts but was more easily repaired than the netting, making them more suited for short term projects. Our results showed reduced interaction of toads with the tarp fence, which could be linked to its opacity as shown in chapters 4, 5, and 6 of Brehme et al. (2020). This phenomenon could be beneficial if it prevents toads from exhausting themselves trying to climb the fence but could be detrimental if it ends up hindering the guiding function of drift fences.

Polyethylene netting

The longer longevity of polyethylene netting fences makes them more suited for repeated use. A potential drawback of the netting could be an abrasion-linked trauma that was witnessed on the snout of frogs near polyethylene netting fences by Gould *et al.* (2024), although they did not witness the trauma happening. We did not observe such trauma during our trials but if the netting was proven to cause such abrasion, the material should then be avoided. Polyethylene netting was the most complex fence to set up. That being said, when compared to the least complex fence (wire meshing), operators gave a very diverse feedback on how easy it was to set up. Accounting for the fact that it was the first time the operators used the polyethylene fence, the added complexity of this design might not be a major drawback in the end, especially for experienced operators.

CONCLUSION

For repeated use, we recommend 60 cm polyethylene netting fences with a 10 cm, 90° overhang as they are the best combination of effectiveness, cost and durability. For punctual use and if wind/ truck traffic is not a problem, we recommend 60 cm tarp fences with a 10 cm 90° overhang since this option is three times cheaper than the polyethylene netting.

ACKNOWLEDGEMENTS

This study was funded by the French Collectivité européenne d'Alsace. We thank Mila WITCHER for their work in helping building the experimental arenas, running the experimental trials and sampling behaviours from pictures, and every other student that occasionally helped with running the experimental trials. We also thank the Ligue de Protection des Oiseaux Alsace association and the Eurométropole d'Alsace for their collaboration. Finally, we thank the Massif forestier de Strasbourg Neuhof – Illkirch Graffenstaden nature reserve, the Office National des Forêts, as well as Mr & Mrs Moge and Mr Walther for allowing us access to the breeding ponds present on their properties.

AUTHORS CONTRIBUTION

Meven Le Brishoual, Claude Miaud and Jonathan Jumeau conceived the study and designed the experimental protocols. Meven Le Brishoual conceived the experimental arenas, built them with Nathan Dehaut. Meven Le Brishoual, Clara Tanvier and Nathan Dehaut collected the data in the field. Meven Le Brishoual and Clara Tanvier analysed the data. Meven Le Brishoual and Clara Tanvier drafted the manuscript. Jonathan Jumeau, Claude Miaud and Nathan Dehaut gave critical feedback on the manuscript. All authors have read and approved this version of the manuscript for publication and agree to be held accountable for their contributed part of the work.

DATA AVAILABILITY

All of the data used for the statistical analyses are available online from the Zenodo repository https://doi.org/10.5281/zenodo.19371094 (Le Brishoual et al. 2026).

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

REFERENCES

Altmann J (1974) Observational study of behavior: sampling methods. Behaviour 49: 227–267.

Arnfield H, Grant R, Monk C, Uller T (2012) Factors influencing the timing of spring migration in common toads (*Bufo bufo*). Journal of Zoology 288: 112–118.

Arntzen JW, Oldham RS, Latham DM (1995) Cost effective drift fences for toads and newts. Amphibia-Reptilia 16: 137–145.

Association Les Piverts (2024) Sauvetage des amphibiens en migration nuptiale - Site du Hammerweier (Bas-Rhin) - Bilan de campagne 2024.

Barnes WJP, Goodwyn PJP, Nokhbatolfoghahai M, Gorb SN (2011) Elastic modulus of tree frog adhesive toe pads. Journal of Comparative Physiology A 197: 969–978.

Beaune D (2019) Les traversées manuelles de crapauds communs par des bénévoles peuvent-elles sauver les populations de la mortalité routière ? Bulletin de la Société Herpétologique de France 171: 1–12.

Beebee TJC (2013) Effects of road mortality and mitigation measures on amphibian populations. Conservation Biology 27: 657–668.

Bennett AF (1984) Thermal dependence of muscle function. American Journal of Physiology - Regulatory Integrative and Comparative Physiology 247.

Bettencourt-Amarante S, Furet R, Abensur R, Herrel A (2024) Does habitat modification impact morphology, performance, and inflammatory responses in an amphibian with limited dispersal capacity (*Lisssotriton helveticus*)? Ecology and Evolution 14

Boissinot A, Etave M, & Lourdais O (2023) Les trognes, des arbres-habitats pour les amphibiens de la Réserve Naturelle Régionale du Bocage des Antonins. 50ème Congrès de la Société Herpétologique de France – Erquy, France.

Brehme C, Fischer R, Tracey J, Ewing B, Hobbs M, Launer A, Adelsheim E, Barnies S, Vaughan C, Edgarian T, Kingston J, Sebes J (2020) Research to inform Caltrans best management practices for reptile and amphibian road crossings. USGS Cooperator Report to California Department of Transportation, Division of Research, Innovation and System Information, 65A0553

Brehme CS, Tracey JA, Ewing BAI, Hobbs MT, Launer AE, Matsuda TA, Adelsheim EMC, Fisher RN (2021) Responses of migratory amphibians to barrier fencing inform the spacing of road underpasses: a case study with California tiger salamanders (*Ambystoma californiense*) in Stanford, CA, USA. Global Ecology and Conservation e01857.

Carr LW, Fahrig L (2001) Effect of road traffic on two amphibian species of differing vagility. Conservation Biology 15: 1071–1078.

Cayuela H, Valenzuela-Sánchez A, Teulier L, Martínez-Solano Í, Léna J-P, Merilä J, Muths E, Shine R, Quay L, Denoël M, Colbert J, Schmidt BR (2020) Determinants and consequences of dispersal in vertebrates with complex life cycles : a review of pond-breeding amphibians. The Quarterly Review of Biology 95: 1–36.

Chanson J., Neam K., Stengel C, Swandby J., Hobin L., Long B., Lamb B. (2023) State of the World's Amphibians: The Second Global Amphibian Assessment. Texas

Collett TS (1982) Do toads plan routes? A study of the detour behaviour of *Bufo viridis*. Journal of Comparative Physiology: 261–171.

Conan A, Fleitz J, Garnier L, Le Brishoual M, Handrich Y, Jumeau J (2022) Effectiveness of wire netting fences to prevent animal access to road infrastructures: an experimental study on small mammals and amphibians. Nature Conservation 47: 271–281.

Conan A, Le Brishoual M, Garnier L, Fleitz J, Dehaut N, Enstipp M, Jumeau J, Handrich Y (2023) Efficacy of permanent wildlife fences as barriers to amphibian movement. Frontiers in Ecology and Evolution 11: 1074072.

Crawford N, Endlein T, Pham JT, Riehle M, Jon Barnes WP (2016) When the going gets rough-studying the effect of surface roughness on the adhesive abilities of tree frogs. Beilstein Journal of Nanotechnology 7: 2116–2131.

Csutoros A (2025). Observations du comportement de recherche de hauteur chez le Triton palmé *Lissotriton helveticus* en Ille-et-Vilaine (France). *Bulletin de La Société Herpétologique de France*, *186*, 1–4.

Dall'antonia P, Sinsch U (2001) In search of water: Orientation behaviour of dehydrated natterjack toads, *Bufo calamita*. Animal Behaviour 61: 617–629.

Dodd CK (1991) Drift fence-associated sampling bias of amphibians at a Florida sandhills temporary pond. Journal of Herpetology 25: 296.

Eggert C. (2019) Amphibiens et routes. Available from: https://lashf.org/amphibiens-et-routes/ (November 12, 2025).

Emerson, S. B. (1978). Allometry and Jumping in Frogs: Helping the Twain to Meet. *Evolution*, *32*(3), 551.

Federle W, Barnes WJP, Baumgartner W, Drechsler P, Smith JM (2006) Wet but not slippery: Boundary friction in tree frog adhesive toe pads. Journal of the Royal Society Interface 3: 689–697.

Friard O, Gamba M (2016) BORIS: a free, versatile open-source event-logging software for video/audio coding and live observations. Methods in Ecology and Evolution 7: 1325–1330.

Ganet A, Vacher J-P (2012) Évaluation de l'efficacité des dispositifs de protection routière pour les amphibiens et identification des zones à enjeux dans le Haut-Rhin Décembre 2012.

Gibbs JP, Shriver G (2005) Can road mortality limit populations of pool-breeding amphibians? Wetlands Ecology and Management 13: 281–289.

Glista DJ, Devault TL, Dewoody JA (2008) Vertebrate road mortality predominantly impacts amphibians. Herpetological Conservation and Biology 3: 77–87.

Gould J, Callen A, Knibb G, Donelly R, Schmahl K, Maynard C, Sanders S, Lemckert F, Mchenry C, Stow A (2024) Learning from past designs: improving amphibian fences using an adaptive management approach. Wildlife Research 51.

Gunderson AR, Leal M (2015) Patterns of thermal constraint on ectotherm activity. The American Naturalist 185: 653–664.

Helldin JO, Petrovan SO (2019) Effectiveness of small road tunnels and fences in reducing amphibian roadkill and barrier effects at retrofitted roads in Sweden. PeerJ 2019: e7518.

Hels T, Buchwald E (2001) The effect of road kills on amphibian populations. Biological Conservation 99: 331–340.

Hertwig I, Sinsch U (1995) Comparative toe pad morphology in marsupial frogs (genus *Gastrotheca*): Arboreal versus ground-dwelling species. Copeia: 38–47.

Huijser M, Duffield J, Neher C, Clevenger A, McGuire T (2022) Cost-Benefit Analyses of Mitigation Measures Along Highways for Large Animal Species: An Update and an Expansion of the 2009 Model.

Huijser MP, Duffield JW, Clevenger AP, Ament RJ (2009) Cost–Benefit Analyses of Mitigation Measures Aimed at Reducing Collisions with Large Ungulates in the United States and Canada: a Decision Support Tool.

Huijser MP, Fairbank ER, Camel-Means W, Graham J, Watson V, Basting P, Becker D (2016) Effectiveness of short sections of wildlife fencing and crossing structures along highways in reducing wildlife-vehicle collisions and providing safe crossing opportunities for large mammals. Biological Conservation 197: 61–68.

Isambert J, Didier S (2024) Bilan de campagne de sauvetage des amphibiens dans le Bas-Rhin. Printemps 2024.

Iuell B, Bekker H, Cuperus R, Dufek J, Fry G, Hicks C, Hlavác V, Keller V, Rossel C, Sangwire T, Tørsløv N, Wandall BLM (2003) Wildlife and traffic: A European Handbook for Identifying Conflicts and Designing Solutions.

Jochimsen D, Peterson CR, Andrews K (2013) A literature review of the effects of roads on amphibians and reptiles and the measures used to minimize those effects. USDA Forest Service - General Technical Report PNW: 1–78.

Joly P (2019) Behavior in a changing landscape: using movement ecology to inform the conservation of pond-breeding amphibians. Frontiers in Ecology and Evolution 7: 155.

Jumeau J (2017) Les possibilités de dispersion et éléments d'habitat-refuge dans un paysage d'agriculture intensive fragmenté par un réseau routier dense : le cas de la petite faune dans la plaine du Bas-Rhin. Université de Strasbourg.

Langowski JKA, Dodou D, Kamperman M, van Leeuwen JL (2018) Tree frog attachment: Mechanisms, challenges, and perspectives. Frontiers in Zoology 15: 1–21.

Mazerolle MJ, Huot M, Gravel M (2005) Behavior of amphibians on the road in response to car traffic. Herpetologica 61: 380–388.

Morand A. (2019) Amphibiens et dispositifs de franchissement des infrastructures de transport terrestre. 1–58 pp.

Moreno-Rueda G, Requena-Blanco A, Zamora-Camacho FJ, Comas M, Pascual G (2020) Morphological determinants of jumping performance in the Iberian green frog. Current zoology 66: 417–424.

Muller B, Schwarzkopf L (2017) Success of capture of toads improved by manipulating acoustic characteristics of lures. Pest Management Science 73: 2372-2378.

Munteanu AM, Starnberger I, Pašukonis A, Bugnyar T, Hödl W, Fitch WT (2016) Take the long way home: Behaviour of a neotropical frog, *Allobates femoralis*, in a detour task. Behavioural Processes 126: 71–75.

Navas CA, James RS, Wakeling JM, Kemp KM, Johnston IA (1999) An integrative study of the temperature dependence of whole animal and muscle performance during jumping and swimming in the frog Rana temporaria. Journal of Comparative Psychology B 169: 588–596.

Orłowski G, Ciesiołkiewicz J, Kaczor M, Radwańska J, Żywicka A (2008) Species composition and habitat correlates of amphibian roadkills in different landscapes of south-western Poland. Polish Journal of Ecology 4: 659–671.

Oromí N, Sanuy D, Sinsch U (2010) Thermal ecology of natterjack toads (*Bufo calamita*) in a semiarid landscape. Journal of Thermal Biology 35: 34–40.

Puky M (2003) Amphibian mitigation measures in Central-Europe. Ecotoxicology Lead Campus Program Publications: 413–429.

Sacchi R, Cigognini R, Gazzola A, Bernini F, Razzetti E (2015) Male calling activity in syntopic populations of *Rana latastei* and *Rana dalmatina* (*Amphibia*: *Anura*). Italian Journal of Zoology 82: 124–132.

Saltzman H, Zacharatos M, Gruberg ER (2004) Recognition of apertures in overhead transparent barriers by leopard frogs. Brain, Behavior and Evolution 64: 11–18.

Schmidt BR, Zumbach S (2008) Amphibian road mortality and how to prevent it: A review. In: Mitchell JC, Jung Brown RE, Bartolomew B (Eds), Urban Herpetology. St. Louis, 131–141.

Smith LL, Dodd CK (2003) Wildlife mortality on U.S. highway 411 across Paynes Prairie, Alachua County, Florida. Florida Scientist 66: 128–140.

Smith RK, Sutherland WJ (2014) Amphibian conservation: global evidence for the effects of interventions. Exeter. Pelagic Publishing. Speybroeck J, Beukema W, Bok B, Van der Voort J, Llian V (2018) Guide Delachaux des amphibiens et reptiles de France et d'Europe. Delachaux et Niestlé.

Swoap SJ, Johnson TP, Josephson RK, Bennett AF (1993) Temperature, muscle power output and limitations on burst locomotor performance of the lizard *Dipsosaurus dorsalis*. Journal of Experimental Biology: 185–197.

Testud G, Fauconnier C, Labarraque D, Lengagne T, Le Petitcorps Q, Picard D, Miaud C (2020) Acoustic enrichment in wildlife passages under railways improves their use by amphibians. Global Ecology and Conservation 24 e01252.

Woltz HW, Gibbs JP, Ducey PK (2008) Road crossing structures for amphibians and reptiles: Informing design through behavioral analysis. Biological Conservation 141: 2745–2750.

Zug, G. R. (1985). Anuran locomotion: Fatigue and jumping performance. *Herpetologica*, *41*(2), 188–194.