Manuscript title:

Effectiveness of small road tunnels and fences in reducing amphibian roadkill and barrier effects; case studies of retrofitted roads in Sweden

Authors:

Jan Olof Helldin[1] and Silviu O. Petrovan[2,3]*

1) *Swedish Biodiversity Centre, SLU, Uppsala, Sweden*
2) *Department of Zoology, University of Cambridge, Cambridge, UK*
3) *Froglife, Peterborough, UK*

* *Corresponding author* j-o.helldin@slu.se

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.27530v1 | CC BY 4.0 Open Access | rec: 11 Feb 2019, publ: 11 Feb 2019

Abstract

Although schemes to reduce road impacts on amphibians have been implemented for decades in Europe, several aspects on the effectiveness of such schemes remain poorly understood. Particularly in northern Europe, including Sweden, there is a widespread lack of available information on road mitigation for amphibians, which is hampering implementation progress and cost-effectiveness analyses of mitigation options. Here we present data derived from systematic counts of amphibians during spring migration at three previous hot-spots for amphibian roadkill in Sweden, where amphibian tunnels with guiding fences have now been installed. We used the data in combination with a risk model to estimate the number of roadkills and successful crossings before vs. after mitigation and mitigated vs. adjacent non-mitigated road sections. The estimated number of amphibians killed or at risk of being killed by car traffic decreased by 91–100% and the estimated number successfully crossing the road increased by 25–340% at mitigated road sections. Data however suggested fence-end effects that may moderate the reduction in roadkill. We discuss possible explanations for the observed differences between sites and construction types, and implications for amphibian conservation. We show how effectiveness estimates can be used for prioritizing amphibian passages along the existing road network. Finally, we emphasise the importance of careful monitoring of amphibian roadkill and successful crossings when new amphibian passages are constructed.

1. Introduction

Amphibian populations may be severely impacted by road mortality and barrier effects of roads and traffic (Hels & Buchwald, 2001; Jaeger & Fahrig, 2004; Nyström *et al.*, 2007; Beebee 2013). Mass mortalities of amphibians often occur where roads and car traffic cut across annual migration routes between hibernation and breeding habitats. Roadkill, habitat loss and the generally harsh environment for amphibians along roads can also lead to avoidance and barrier effects, preventing them from reaching crucial habitats or resources. In attempts to reduce such negative effects, road mitigation measures have been developed and implemented for over 40 years in Europe (Langton 2015). However, monitoring of such measures is often lacking or insufficient (e.g., focusing solely on usage) and previous studies have shown varying results (e.g., Brehm, 1989; Meinig, 1989; Zuiderwijk, 1989; Puky & Vogel, 2003; Mechura *et al.*, 2012;

Faggyas & Puky, 2012; Van Der Grift *et al.*, 2017; Matos *et al.*, *in press*), so numerous aspects on the actual effectiveness of road mitigation schemes for amphibians remain poorly understood. At the same time, populations of amphibians continue to decline in Europe, including some of the main target species for road mitigation, the common toad *(Bufo bufo)*, the common frog *(Rana temporaria)* and the great crested newt (*Triturus cristatus*) (Bonardi *et al.*, 2011; Beebee, 2013; Petrovan & Schmidt, 2016; Kyek, Kaufmann & Lindner, 2017). In northern Europe, including Sweden, there is a widespread lack of available information on road mitigation for amphibians, despite the very well developed road network as well as the potentially complex effects of the harsher climate on microclimatic conditions inside road tunnels or other unforeseen aspects. The absence of structured information and evidence of effectiveness is hampering implementation progress and much needed cost-effectiveness analyses of mitigation options.

To minimise the road impacts on amphibians, road managers in and near Stockholm (the Swedish Transport Administration and Stockholm Municipality) constructed passages for amphibians at three hot-spots for amphibian roadkill, i.e., where large concentrations of amphibians were killed on roads, particularly during spring migration, and thus were considered to be road sections in critical need of ecological mitigation. The passages where in the form of permanent tunnels with double-sided guiding fences intended to lead the amphibians safely under the road in both directions. The constructions largely followed the European (Iuell *et al.*, 2003) and Swedish (Eriksson, Sjölund & Andrén, 2000; Banverket, 2005) guidelines for design and dimensions, however with tunnels narrower than the recommended minimum diameter 0,6–1 m and with distance between neighboring tunnels in some cases longer than the recommended maximum of 30–60 m.

Before and after the construction of these passages, the number and location of amphibians on the road as well as along the fences and in the tunnels were recorded, as the basis for planning of the mitigation constructions and monitoring of their effectiveness. Here we summarise the results of these counts, and discuss the implications in terms of reduced roadkill and barrier effect, differences between constructions, and improved amphibian conservation. We propose a baseline for prioritizing amphibian passages along the existing road network, and suggest some directions for further studies that would support the planning of amphibian mitigation schemes.

2. Material and methods

2.1 Study sites and available field data

The three monitored sites – Skårby, Kyrksjölöten and Skeppdalsström – are similar in a number of respects. The roads are all of intermediate size (7-8 m wide, ca 3,000-9,000 vehicles per average day; Table 1), of importance mainly for local and commuting traffic in Stockholm metropolitan area (Fig. 1). The landscape is a small-scale valley terrain at 10–30 m elevation, with a mix of forest, farmland and housing/garden areas. The mitigated road sections all have an important amphibian breeding wetland of around 5–10 ha nearby and main overwintering habitat, typically woodland, on the opposite side of the road (Fig. 2–4). Before mitigation, the road sections were well known hot-spots for amphibian roadkill during spring migration. The amphibian species diversity in the region is limited, with only five species occurring; common toad, common frog, moor frog (*Rana arvalis*), smooth newt (*Lissotriton vulgaris*) and great crested newt.

The mitigation systems are roughly similar in terms of dimensions of tunnels and fences and length of road section mitigated, while there are some differences in exact dimensions and material of the constructions (Table 1). At all sites, tunnels were impacted by running or standing water to a varying degree during the studies (Table 1).

Live and dead amphibians were counted along the road prior to construction of the passage, aiming to identify the most critical road sections for mitigation and to locate major migration routes where tunnels should be placed. Amphibians were also counted post-mitigation, along the road, along fences and in tunnels, to assess the anticipated reduction in roadkill and evaluate the use of the tunnels. While the field efforts varied between sites and periods (Table 2), all data collection was conducted during peak spring migration, with methods that could be considered comparable in terms of number of amphibians found per time and road interval. Data collection methods included visual search on the road and along fences, pitfall trapping along temporary fences, net trapping in tunnels and timelapse camera trapping in tunnels. Methods applied at each site are described in more detail in Supplemental Article S1.

2.2 Data treatment and analyses

We standardised the available data on amphibian counts on and near the roads, along fences and in tunnels to be able to compare, as far as possible, each site before and after mitigation and the mitigated road section with adjacent non-mitigated sections. We summarised the number of amphibians found on and near the road (including along temporary fences at site 2) per night (site 1) or evening (site 2–3) and 50m road interval, assuming that these data were collected with a similar effort over the road section searched, and with a similar effort before and after mitigation, within each site. We however acknowledge that the method used along the temporary fence at site 2 was too different to allow a direct comparison with non-mitigated sections for that site.

To be able to tentatively compare the performance of different tunnels at a site, we calculated the number through each tunnel per night (at site 1) or number of movements (in + out) and the net number through each tunnel per 24h-period (at site 2–3). To assess the number of amphibians successfully crossing a mitigated road section through the tunnels we summarised the net number through all tunnels at the site.

To assess the number of amphibians killed and the number successfully crossing a non-mitigated road section, we used the relationship presented by Hels & Buchwald (2001) on the risk of getting killed for an amphibian on the road depending on average traffic intensity and species (Fig. 5). According to this relationship, a proportion of the amphibians found alive on and near the road attempting to cross it should have made it successfully to the other side even without being rescued, and concomitantly, the number of amphibians found dead on the road should represent also a certain number that survived and managed to cross.

In site 1, newts made up ca 98% of amphibians observed, so we analysed only data on newts from this site, and pooled the two newt species in the analyses. Most of the newts found when searching the road were dead (ca 72%). Using the information presented Hels & Buchwald (2001) in combination with average traffic intensity and species analysed, we estimated that 62% of newts trying to cross the road surface at the site would get killed by traffic (as read in Fig. 5), and accordingly assumed that each newt found dead represented (1/0.62)-1 = 0.61 newt that had managed to cross.

In site 2, common toads made up ca 99% of amphibians observed, and accordingly we analysed only data on common toad. Most of the toads found when searching the road were dead (ca 82%), while all toads found or captured along the temporary fence were alive. We estimated a 70% risk of getting traffic killed for toads trying to cross the road surface at the site (Fig. 5), and assumed that each toad found roadkilled represented (1/0.70)-1 = 0.43 toads that had crossed successfully and that each toad found along the temporary fence represented 1-0.70 = 0.30 toad that would have managed to cross the road, had the fence not been in place.

In site 3, significant numbers were found of 4 species (all except great crested newt), so we included all amphibians in the analyses for that site. Most amphibians found on or approaching the road were alive (ca 83%). We assumed that on average 75% (newts 79%, toads and frogs 72%; Fig. 5) of amphibians trying to cross the road surface would get killed by traffic and that each amphibian rescued represented 1-0.75 = 0.25 amphibian that would have managed to cross the road, had the rescue not taken place.

3. Results

The number of amphibians found on or heading for the road, i.e. animals killed or at risk of being killed by car traffic, during spring migration decreased at mitigated road sections at all three sites (Fig. 6). The estimated number of individual amphibians saved by the mitigation measures ranged from 25 to >200 per night at the three sites (Table 3), corresponding to a 91–100% decrease in roadkilled amphibians along mitigated road sections. Outside mitigated road sections the changes from before to after mitigation were smaller and more variable; the number of amphibians on the road decreased by 33% at site 1, increased by over 300% at site 2, while there was virtually no change at site 3. At site 2, the number of amphibians on the road peaked just outside of the fence-ends (intervals 8 and 15–17; see Fig. 6). At site 1 and 2, some individuals were found on the road just inside the fence-ends (east end at site 1, both ends at site 2; Fig. 6). No amphibians were found on a fenced road section >100 m from a fence-end.

The number of amphibians passing through the tunnels varied greatly between sites (3000% difference; Table 4), largely following the number that was killed before mitigation, i.e., many more at site 1. The estimated number of amphibians successfully crossing the road increased at mitigated sections, ranging from 2–180 more individuals per night (Table 5), corresponding to a 25–340% increase compared to the situation before mitigation. In addition, the estimated number successfully crossing along non-mitigated sections differed between before and after mitigation, and over the entire site (mitigated + non-mitigated road sections combined) the mitigation implementation resulted in 2–162 more individuals crossing the road per night (Table 5), or a 16–340% increase.

The number of amphibians passing through the tunnels also varied greatly among the tunnels at sites 1 and 3 (Table 4). Tunnel no. 2 at site 3 stood out by the large discrepancy between the high number of amphibians moving in and out of the tunnel entrance and the low net number passing through. This tunnel had a shallow pool in the northern (entrance) side, while the southern (exit) side was completely submerged.

4. Discussion

The compiled results from the monitoring of amphibian passages at the three sites (Skårby, Kyrksjölöten, Skeppdalsström) indicate that the passages were effective in reducing the number of roadkilled amphibians during spring migration, compared to a situation before mitigation measures were implemented. No or very few amphibians were found on the fenced road sections, where prior to mitigation amphibians had been killed in the hundreds or thousands each spring. These results are well in line with those from many other studies, showing significant reductions in amphibian roadkill after the construction of adequate road fences (e.g., Meinig, 1989; Dodd, Barichivich & Smith, 2004; Jochimsen *et al.*, 2004; Stenberg & Nyström, 2009; Malt, 2011; Matos *et al.*, 2017; Hill *et al.*, 2018; Matos *et al.*, *in press*).

However, the data from at least two of our sites suggested the presence of fence-end effects (Huijser *et al.*, 2016) which may influence the overall reduction in amphibian roadkill. Peaks in numbers on the road just outside fence-ends at site 2 suggest that some individuals following the fence by-passed the ends, despite the angled fence-ends, and that part of the mortality was merely transferred from fenced to unfenced road sections. The increase in amphibians on the entire unfenced part of the road at site 2 may also be explained by individuals finding new migration routes when the previous ones have been occupied by fences, and tunnels are avoided or simply not encountered (though we also see several alternative explanations to that pattern; see below). Furthermore, at site 1 and site 2 some amphibians cut into the mitigated road section near the fence-ends. This may be an effect of animals moving diagonally over the road, not being strictly directional in their movements, or following the road along curbs or other minor structures into the fenced section. Nearer to the middle of the fenced sections no amphibians were found on the road, and accordingly, in the central parts of the mitigated road sections the decrease in roadkilled amphibians was 100% at all three sites.

These fence-end effects, and the fact that many amphibians crossed and were killed on the road outside the fenced sections, imply that longer fences are likely to result in a larger reduction in roadkill (Buck-Dobrik & Dobrick, 1989; Huijser *et al.*, 2016). While this notion may seem trivial, it has important implications for management (see below).

It is imperative that the effectiveness of amphibian passages in the form of under-road tunnels with associated guiding fences are not only assessed on the basis of the reduction in roadkill but also on the number of animals making it successfully to the other side of the road (Jochimsen *et al.*, 2004; Schmidt & Zumbach, 2008). Previous studies have indicated that many amphibians reaching the fences do not find their way through the tunnels, either because the tunnels are too widely separated or the tunnels or guiding structures are inadequate, and as a consequence amphibians may return to the terrestrial habitats without breeding (Allaback & Laabs, 2003; Jochimsen *et al.*, 2004; Schmidt & Zumbach, 2008; Pagnucco *et al.*, 2012). Several European studies have reported proportions of individual toads or newts using tunnels ranging from 3% to 98% of those encountering the guiding fences (Brehm, 1989; Buck-Dobrick & Dobrick, 1989; Langton, 1989; Meinig, 1989; Zuiderwijk, 1989; Mechura *et al.*, 2012; Van Der Grift *et al.*, 2017; Matos *et al.*, 2017, Matos *et al.*, *in press*).

The results from our three sites indicated that the mitigation schemes likely reduced the barrier effects of the roads. We assumed that a certain proportion of amphibians manage to cross a road without getting killed by traffic, that most amphibians survive where the traffic intensity is very low, but that the proportion surviving decreases exponentially with increasing traffic (Hels & Buchwald 2001; Jacobson *et al.*, 2016). Importantly however, on all three sites studied, the number of individuals passing through the tunnels in spring exceeded the number estimated to have crossed the road surface successfully over the mitigated section before the mitigation was in place.

Several factors in the technical construction of amphibian passages may affect their effectiveness: width, shape and length of tunnels, distance between tunnels, height and shape of guiding barriers, substrate in tunnels and along barriers, construction material, moisture, vegetation and drainage in and around the passages, and special features such as cover objects, guiding structures at entrances and slotted tops (reviews in Jochimsen *et al.*, 2004; Hamer, Langton & Lesbarrères, 2015; Jackson, Smith & Gunson, 2015). Our data did not allow a systematic analysis of how these factors relate to the passage effectiveness. With the information at hand, we can only speculate about the differences observed. At site 1, many newts were carried through the tunnels by the water running in direction towards the wetland, and at site 3, standing water in one of the tunnels appeared to attract many amphibians to the tunnel entrance but blocked the tunnel for actual crossings. It has been suggested that shallow standing or running water in and around tunnels will attract amphibians and help them finding their way through (Rosell *et al.*, 1997; Eriksson, Sjölund & Andrén, 2000; Jochimsen *et al.*, 2004; Schmidt & Zumbach, 2008), while high water levels make tunnels impassable (Buck-Dobrick & Dobrick, 1989; Rosell *et al.*, 1997; Jochimsen *et al*., 2004). Water levels may thus have significant but complex impact on amphibian passage effectiveness. Additionally, the water and soil inside and adjacent to amphibian tunnels can suffer high pollution levels with road surface contaminants including salt used for deicing roads as well as various metals and other substances (White, Mayes & Petrovan, 2017). At site 2, the tunnels were longer and the distance between the tunnels longer, which may explain a bypass effect, i.e., peaks in animals on the road just outside fence-ends. Previous studies suggest that long tunnels and long fences without tunnels make amphibians give up and turn back (Zuiderwijk, 1989; Jochimsen *et al.*, 2004; Van Der Grift *et al.*, 2017; Jackson, Smith & Gunson, 2015; Hill *et al*., 2018; Matos *et al*., *in press*); these individuals may eventually try crossing the road on another spot. There were significant movements in and out of the tunnels at this site, which may indicate that animals hesitated to pass through. However, the total numbers actually crossing through the tunnels were similar to the estimated number killed or crossing the fenced section before mitigation (58.8/24h vs. 32.1+13.8=45.9/night).

There are several plausible explanations for the changes in the number of amphibians on the road outside mitigated sections (most pronounced at site 1 and 2), other than the potential bypass effect described above. The most obvious is that the field effort at some sites and time periods was insufficient (three nights or less for data collection) and the data therefore were influenced by random events. Another is that the fieldwork methods were in fact not similar enough with regard to how the basic method was applied in practice to allow the data standardisation and comparisons. The changes observed may also depend on annual differences in population numbers or temporal migration patterns. In this case, the effect sizes on mitigated sections can be adjusted according to the changes on non-mitigated sections. It is however important to note that the non-mitigated sections studied were not true controls (comparators), as they were not unaffected by the mitigation measure (the intervention).

The standardisation of data required a number of assumptions and simplifications that may have introduced errors. We adopted an approach where we tried finding the unifying patterns in a number of studies of amphibian passages conducted with slightly different aims, budgets, staffing and time frames. Despite these limitations, we believe that the general picture given by these studies, before vs. after mitigation and along vs. outside the mitigated road section, contributes significantly to the knowledge of how amphibian passages at roads can reduce roadkill and barrier effects on amphibians during spring migration.

5. Implications for management

There is scant evidence in literature that the construction of amphibian passages will lead to long-term conservation of amphibian populations (Beebee, 2013; Smith, Meredith & Sutherland, 2018), and also for our three sites it is difficult to be certain to what degree the observed reductions in roadkill and barrier effect will have a significant and long-lasting effect on the population level. However, the estimated number of newts saved by the mitigation system (>200 individuals per peak migration night) and the number of newts crossing through the tunnels (ca 180 per peak migration night) at site 1 (Skårby) are each in the same order of magnitude as the total estimated number of breeding newts at the site (2,000-2,300 individuals, assuming that there are around 10 peak migration nights per season; Peterson & Collinder, 2006). It is reasonable to believe that such an improvement in survival significantly benefits the conservation of the local newt populations.

As a contrast, the low number of amphibians successfully crossing through the tunnels at site 3 (Skeppdalsström) – ca 10 individuals per night, an increase with only 2 per night compared to what may have crossed the road successfully without any mitigation – may appear discouraging. Neither the reduction in the number killed (some 25 per peak migration night) at the site can sum up to anywhere near the total estimated number of amphibians breeding (ca 1,300 individuals; Andersson & Lundberg 2015). The results from site 2 (Kyrksjölöten) indicate that many more toads manage to cross the road alive using the tunnels compared to before mitigation, but these results cannot be put in relation to any estimated population size, and the conclusion regarding the benefit to conservation is confused by the possible bypass effects (see above).

On the other hand, it is possible that even a minor improvement may be enough to reverse a negative population trend if the factor causing it is not rapidly increasing, and the traffic density on these sites should largely follow the national trend with an increase of <1% per year (Trafikanalys, 2013). Moreover, if the additional animals reaching the wetland after mitigation manage to contribute to the reproduction, their numbers will soon multiply.

However, it is important to point out that there should be a minimal level of road traffic where amphibian passages of the kind here described need to be considered, as implied by the relationship between traffic intensity and risk of getting killed described by Hels & Buchwald (2001; Fig. 5). On roads with little traffic many amphibians are likely to cross the road without being killed, and an amphibian passage with fences that hinders some of these movements may lead to a decrease in the number of successful crossings, and cause more harm than good (Jaeger & Fahrig, 2004; Jochimsen *et al.*, 2004; Schmidt & Zumbach, 2008; Pagnucco *et al.*, 2012). The cut-off point depends on the combination of traffic intensity and effectiveness of passages.

Using the data from the present cases, and assuming a constant passage rate through tunnels, the breakeven point for site 1 would be at a risk of around 45%, corresponding to a hypothetical average daily traffic of ca 1,000 vehicles. In other words, had the traffic been <1,000 vehicles, the construction of the passage would have led to fewer amphibians reaching the breeding pond, i.e., an increased barrier effect. For site 3, where the increase in successful crossings was small, the breakeven would be at ca 70% risk, or a hypothetical traffic of ca 6,000 vehicles. (The data from site 2 did not allow a similar assessment due to the increase in amphibians killed on non-mitigated sections.)

We acknowledge that these calculations, as well as all data treatment in our work, rely heavily on Hels & Buchwald´s risk model for amphibians. While their study is well conducted, the results are based on few species and limited observations, and as far as we know has not been replicated or the model predictions empirically tested. Given the need for road managers to know under what circumstances the construction of amphibian passages is motivated, and when not, we strongly recommend further study of the relation between road characteristics (traffic, width etc.) and the roadkill risk for amphibians when attempting to cross.

At all three sites the mitigation was restricted solely to the most critical road sections (see Fig. 6), despite recommendations in ecological assessments from all sites to include also contiguous sections (Collinder, 2007; Helldin, 2015; Lundberg, 2015). Our results suggest that mitigation (guiding fences and additional tunnels) extending at least some 100 m outside of the most critical road section could minimise end effects and further improve the passage effectiveness. While this may be too late to correct on the current sites, it should be considered in new construction projects.

An alternative approach to decrease fence-end effect could be to fortify fence-ends, for example by modifying the angles or extending fences perpendicularly from the road. Amphibians could potentially be helped in finding and entering tunnels with relatively simple means by installing guiding structures at the tunnel entrances where these are not already in place (site 3). It is however unclear to what degree such adaptations would improve the effectiveness of existing passages.

Amphibian passages tend to be costly, not least when constructed on existing roads, and it is therefore crucial for road managers to know where passages may be critical for amphibian conservation and how passages can best be designed. To build up the knowledge of amphibian passages at roads, the reduction in roadkill and barrier effects should be monitored when new amphibian passages are constructed, or when existing passages are adapted (Hamer, Langton & Lesbarrères, 2015; Helldin, 2017). The monitoring should use comparable methods before and after mitigation, include the quantification of amphibians killed and amphibians successfully crossing, and include a long enough road section to cover any bypass effects. Quality data should be secured by a field effort spanning over multiple years before and after mitigation, and multiple times each year. Results from such studies could be combined in global analyses (e.g., meta-analyses) to explore differences between construction types and trade-offs between the economic investment and expected effect size (cost-efficiency), thereby helping to point out where passages along existing roads are warranted.

Finally, it is important to note that our results only focused on adult breeding migrations in spring, without including the summer and autumn migrations of juveniles away from the breeding ponds. Recent population models indicate that the survival of post-metamorphic juveniles is of fundamental importance for the persistence of amphibian populations (Schmidt & Zumbach, 2008; Petrovan & Schmidt, *in press*). Adults and juveniles using the passages later in the season for leaving the breeding areas may experience dryer tunnels or even water counterflow. Juvenile amphibians may be particularly sensitive to the design of underpasses and associated barrier fences (Schmidt & Zumbach, 2008) given their higher desiccation risk. However, due to their very small size and unpredictable migration timing, juveniles remain very rarely quantified in terms of both road mortality impacts and usage of mitigation systems, despite their crucial role in population dynamics (Petrovan & Schmidt, *in press*). Future studies should prioritise incorporating juveniles in mitigation assessments.

6. Acknowledgements

We thank the following people for collecting and processing field data used in the study: Petter Andersson, Per Collinder, Abel Gonzales, Michael Hartup, Mova Hebert, Anna Koffman, Johanna Lundberg, Terese Olsson, Torbjörn Peterson, Anna Seffel, Lisa Sigg, Nina Syde, Claes Vernerback and Mikael Åsberg. We are particularly greatful to Per Collinder for digging out old Skårby reports, and to all the volunteers at Djurens Ö Wildlife Rescue for backing up the field work at Skeppdalsström. The field work was financed by the Swedish Transport Administration (Skårby and Skeppdalsström) and Stockholm Municipality (Kyrksjölöten). The study was financed by the Swedish Transport Administration, as part of the TRIEKOL project (http://triekol.se/home-eng/).

7. References

Allaback ML, Laabs DM. 2002. Effectiveness of road tunnels for the Santa Cruz long-toed salamander. *Transactions of the Western Section of the Wildlife Society* 38/39:5–8.

Andersson P, Lundberg J. 2015. Groddjursinventering och flytt vid väg 222, Skeppdalsström, Värmdö kommun, Stockholms län. *Report from Trafikverket* dated 2015-06-10. (In Swedish)

Banverket. 2005. Vilda djur och infrastruktur – en handbok för åtgärder. *Banverket Miljösektionen rapport* 2005:5, *Vägverket publikation* 2005:72. (In Swedish) https://trafikverket.ineko.se/Files/sv-SE/12025/RelatedFiles/2005_72_vilda_djur_och_infrastruktur_en_handbok_for_atgarder.pdf

Beebee TJC. 2013. Effects of Road Mortality and Mitigation Measures on Amphibian Populations. *Conservation Biology* 27(4):657–668. https://doi.org/10.1111/cobi.12063

Bonardi A, Manenti R, Corbetta A, Ferri V, Fiacchini D, Giovine G, Macchi S, Romanazzi E, Soccini C, Bottoni L, Padoa-Schioppa E, Ficetola GF. 2011. Usefulness of volunteer data to measure the large scale decline of "common" toad populations. *Biological Conservation* 144:2328–2334.

Brehm K. 1989. The acceptance of 0.2-metre tunnels by amphibians during their migration to the breeding site. In: Langton TES, ed. *Toad Tunnel Conference: Amphibians and Roads.* Proceedings of the Toad Tunnel Conference, Rendsburg, Federal Republic of Germany, 7–8 January 1989, 29–42.

Buck-Dobrick T, Dobrick R. 1989. The behaviour of migrating anurans at a tunnel and fence system. In: Langton TES, ed. *Toad Tunnel Conference: Amphibians and Roads.* Proceedings of the Toad Tunnel Conference, Rendsburg, Federal Republic of Germany, 7–8 January 1989, 137–143.

Collinder P. 2007. Skårby åtgärdsförslag. Report *from Ekologigruppen AB* 2007-07-04. (In Swedish)

Dodd CK, Barichivich WJ, Smith LL. 2004. Effectiveness of a barrier wall and culverts in reducing wildlife mortality on a heavily traveled highway in Florida. *Biological Conservation* 118:619–631.

Eriksson O, Sjölund A, Andren C. 2000. Amphibians and Roads. *Swedish National Road Administration Publication* 7, Vägverket, Borlänge, Sweden.

Faggyas S, Puky M. 2012. Construction and preliminary monitoring results of the first ACO Wildlife Pro amphibian mitigation systems on roads in Hungary. *Állattani Közlemények* 97:85–93. http://real-j.mtak.hu/8022/1/AllataniKozlemenyek_97.pdf (In Hungarian, with English summary)

Hamer AJ, Langton TES, Lesbarrères D. 2015. Making a safe leap forward: Mitigating road impacts on amphibians. In: van der Ree R, Smith DJ, Grilo C, eds. *Handbook of Road Ecology, First Edition*. John Wiley & Sons Ltd, 261–270.

Helldin JO. 2015. Uppföljning och utvärdering av groddjurstunnlar på Spångavägen. *Report from Calluna AB and Stockholm Stad*. (In Swedish) http://miljobarometern.stockholm.se/content/docs/tema/natur/Groddjur/Groddjurstunnlar%20Spångavägen%20Rapport%202015-10-02.pdf

Helldin J-O. 2017. Metod för uppföljning av groddjursåtgärder vid väg. *Trafikverket publikation* 2017:130. (In Swedish.) https://trafikverket.ineko.se/Files/sv-SE/27451/Ineko.Product.RelatedFiles/2017_130_metod_for_uppfoljning_av_groddjursatgärder_vid_vag.pdf

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

Hill IDC, Rossi CA, Petrovan SO, Hartup M, Clark F, Downie JR. 2018. Mitigating the effects of a road on amphibian migrations: a Scottish case study of road tunnels. *The Glasgow Naturalist* 27, Supplement: The Amphibians and Reptiles of Scotland.

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.

Iuell B, Bekker HGJ, Cuperus R, Dufek J, Fry G, Hicks C, Hlaváč V, Keller V, Rosell C, Sangwine T, Tørsløv N, Le Maire Wandall B. 2003. *COST 341–Wildlife and Traffic: A European Handbook for Identifying Conflicts and Designing Solutions.* KNNV Publishers, Brussels. http://www.iene.info/wp-content/uploads/COST341_Handbook.pdf

Jackson SD, Smith DJ, Gunson K. 2015. Mitigating road effects on small mammals. In: Andrews KM, Nanjappa P, Riley SPD, eds. *Roads and Ecological Infrastructure; Concepts and Applications for Small Animals*, John Hopkins University Press, Baltimore, 177–207.

Jacobson SL, Bliss-Ketchum LL, de Rivera CE, Smith WP. 2016. A behavior-based framework for assessing barrier effects to wildlife from vehicle traffic volume. *Ecosphere* 7(4):e01345. 10.1002/ecs2.1345

Jaeger JAG, Fahrig L. 2004. Effects of road fencing on population persistence. *Conservation Biology* 18:1651–1657. DOI10.1111/j.1523-1739.2004.00304.x

Jochimsen DM, Peterson CR, Andrews KM, Whitfield Gibbons J. 2004. A literature review of the effects of roads on amphibians and reptiles and the measures used to minimize those effects. *Idaho Fish and Game Department and USDA Forest Service report*.

Kyek M, Kaufmann PH, Lindner R. 2017. Differing long term trends for two common amphibian species (Bufo bufo and Rana temporaria) in alpine landscapes of Salzburg, Austria. *PLoS ONE* 12(11): e0187148. https://doi.org/10.1371/journal.pone.0187148

Langton TES. 1989. Tunnels and temperature: results from a study of a drift fence and tunnel system for amphibians at Henley-on-Thames, Buckinghamshire, England. In: Langton TES, ed. *Toad Tunnel Conference: Amphibians and Roads.* Proceedings of the Toad Tunnel Conference, Rendsburg, Federal Republic of Germany, 7–8 January 1989, 145–152.

Langton TES. 2015. A History of Small Animal Road Ecology. Roads and ecological infrastructure: Concepts and applications for small mammals. In: Andrews KM, Nanjappa P, Riley SPD, eds. *Roads and Ecological Infrastructure; Concepts and Applications for Small Animals*. John Hopkins University Press, Baltimore, 7–20.

Lundberg J. 2015. PM Rekommendationer inför anläggande av groddjurstrummor, väg 222, vid Skeppdalsström. *Report from Calluna AB* 2015-02-13. (In Swedish)

Malt J. 2011. Assessing the effectiveness of amphibian mitigation on the Sea to Sky Highway: passageway use, roadkill mortality, and population level effects. *Herpetofauna and Roads Workshop - Is there light at the end of the tunnel?* Vancouver Island University, Nanaimo, Canada, 17–18.

Matos C, Petrovan S, Ward AI, Wheeler P. 2017. Facilitating permeability of landscapes impacted by roads for protected amphibians: patterns of movement for the great crested newt. *PeerJ* 5:e2922; DOI 10.7717/peerj.2922

Matos C, Petrovan SO, Wheeler PM, Ward AI. *in press*. Short-term movements and behaviour govern the use of road mitigation measures by a protected amphibian. *Animal Conservation*. doi:10.1111/acv.12467

Mechura T, Gémesi D, Szövényi G, Puky M. 2012. Temporal characteristics of the spring amphibian migration and the use of the tunnel-barrier system along the Hont and Parassapuszta section of the main road No. 2. between 2009 and 2011. *Állattani Közlemények* 97:77–84. http://real-j.mtak.hu/8022/1/AllataniKozlemenyek_97.pdf (In Hungarian, with English summary)

Meinig H. 1989. Experience and problems with a toad tunnel system in the Mittelgebirge region of West Germany. In: Langton TES, ed. *Toad Tunnel Conference: Amphibians and Roads.* Proceedings of the Toad Tunnel Conference, Rendsburg, Federal Republic of Germany, 7–8 January 1989, 59–66.

Nyström P, Hansson J, Månsson J, Sundstedt M, Reslow C, Broström A. 2007. A documented amphibian decline over 40 years: possible causes and implications for species recovery. *Biological Conservation* 138:399–411.

Pagnucco KS, Paszkowski CA, Scrimgeour GJ. 2012. Characterizing movement patterns and spatio-temporal use of under-road tunnels by long-toed salamanders in Waterton Lakes National Park, Canada. *Copeia* 2012(2):331–340.

Peterson T, Collinder P. 2006. Utvärdering av grodtunnlar vid Skårbydammen, Salem våren 2006. *Report from Ekologigruppen AB*. (In Swedish)

Petrovan SO, Schmidt BR. 2016. Volunteer Conservation Action Data Reveals Large-Scale and Long-Term Negative Population Trends of a Widespread Amphibian, the Common Toad (Bufo bufo). *PLoSONE* 11(10):e0161943.doi:10.1371/ journal.pone.0161943.

Petrovan SO, Schmidt BR. *in press*. Neglected juveniles; a call to incorporate all amphibian life stages into mitigation. *Biological Conservation*.

Puky M, Vogel Z. 2003. Amphibian mitigation measures on Hungarian roads: design, efficiency, problems and possible improvement, need for a co-ordinated European environmental education strategy. *International Conference on Habitat Fragmentation due to Transportation Infrastructure*, IENE, Brussels, Belgium.

Rosell C, Parpal J, Campeny R, Jové S, Pasquina A, Velasco JM. 1997. Mitigation of barrier effect on linear infrastructures on wildlife. In: *Habitat Fragmentation & Infrastructure*. Proceedings of the International Conference on Habitat Fragmentation, Infrastructure and the role of Ecological Engineering, 17–21 September 1995, Maastricht and The Hague, Netherlands. Ministry of Transport, Public Works and Water Management, Delft, Netherlands, 367–372.

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, Missouri, 157-167.

Smith RK, Meredith H, Sutherland WJ. 2018. Amphibian Conservation. In: Sutherland WJ, Dicks LV, Ockendon N, Petrovan SO, Smith RK, eds. *What Works in Conservation 2018*. Open Book Publishers, Cambridge, UK, 9–65. https://www.openbookpublishers.com/product/696

Stenberg M, Nyström P. 2009. Uppföljning av åtgärder för groddjur i Skåne år 2009. *Trafikverket report* 2010:115. (In Swedish) https://trafikverket.ineko.se/Files/sv-SE/12192/RelatedFiles/2010_115_uppfoljning_av_atgarder_for_groddjur_i_skane_ar_2009.pdf

Trafikanalys. 2013. Trafikarbete på svenska vägar – en översyn av skattningsmetoden. *Trafikanalys PM* 3013:8. (In Swedish) https://www.trafa.se/globalassets/pm/2011-2015/2013/pm_2013_8_trafikarbete_paa_svenska_vaegar_-_en_oeversyn_av_skattningsmetoden.pdf

Van der Grift EA, Seiler A, Rosell C, Simeonova V. 2017. Safe roads for wildlife and people. SAFEROAD Final Report. *CEDR Transnational Road Research Programme Call 2013: Roads and Wildlife*. CEDR, Brussels. https://www.saferoad-cedr.org/upload_mm/4/6/b/80eb4659-f6e6-4327-8358-f692b98f3419_CEDR_finalreport.pdf

White KJ, Mayes WM, Petrovan SO. 2017. Identifying pathways of exposure to highway pollutants in great crested newt (Triturus cristatus) road mitigation tunnels. *Water and Environment Journal* 31(3):310-316.

Zuiderwijk A. 1989. Amphibian and reptile tunnels in the Netherlands. In: Langton TES, ed. *Toad Tunnel Conference: Amphibians and Roads.* Proceedings of the Toad Tunnel Conference, Rendsburg, Federal Republic of Germany, 7–8 January 1989, 67–74.

Tables

Table 1. Characteristics of the roads and the amphibian mitigation measures at the three study sites near Stockholm, Sweden. Data on individual tunnels are listed from east to west (see Fig. 2–4).

Site	**1. Skårby**					**2. Kyrksjölöten**		**3. Skeppdalsström**				
Location	59°13'34N 17°43'55E					59°20'53N 17°55'35E		59°18'16N 18°29'32E				
Construction year of mitigation measure	2005, additional tunnels in 2008					2014		2015				
Road												
Name/no	Road 584					Spångavägen		Road 222				
Owner/manager	Swedish Transport Administration					Stockholm Municipality		Swedish Transport Administration				
Mitigated section (m)	300					315		190+110				
Traffic (daily average)[a]	3,000					7,800		8,600				
Width (m)	7					16 [b]		7				
Guiding fences (barriers)												
Hight	40					45		40				
Material	Cement concrete					Polymer concrete		Metal				
Sides	Double sided					Double sided		Double sided				
Location	Parallel to road					Parallel to road		Parallel to road				
End	Wide V-shape					U-shape		Narrow U-shape				
Top	Straight					Angled		Angled				
Tunnels												
Type	Closed top circular					Closed top dome		Closed top circular				
Guiding structure	(T-shape with roof) [c]					I-shape		None				
Number	5					2		5				
Diameter (cm)	40	50	40	40	40	50x32 (both)		30 (all)				
Length (m)	11	?	11	16	12	25	19	10 (all)				
Material [d]	M	Cc	M	M	M	Pc	Pc	P	P	P	M	P
Water [e]	R	R	D	R	R	S	R	D	S	S	D	R
Max water depth (cm)	10	5	–	5	5	5	1	–	30	25	–	5
Distance between (m)	55	55	70	75		180		47	55	215 [f]	115	

a: Data from 2007-2015
b: Including pedestrian and bike lanes
c: Not clear whether these were in place during monitoring
d: M = metal, Cc = cement concrete, Pc = polymer concrete, P = plastic
e: R = running, D = dry, S = standing (at the time for fieldwork)
f: Including distance between mitigated sections

Table 2. Amphibian data collection methods and efforts at the three study sites near Stockholm, Sweden.

Site	1. Skårby		2. Kyrksjölöten		3. Skeppdalsström	
	Before	*After*	*Before*	*After*	*Before*	*After*
Visual search						
Section searched (m)	520		ca 1000		ca 950	
No. of nights	1	4	17	3	7	4
Time period	15–16 April 2004	6–22 April 2008	27 March –9 May 2012	8–15 April 2015	7–19 April 2015	7–18 April 2016
Pitfall trapping along temporary fences						
Section trapped (m)	–		350	–	–	
No. of nights	–		17	–	–	
Time period	–		27 March–9 May 2012	–	–	
Net trapping						
No. of tunnels	–	4	–		–	
No. of nights	–	5	–		–	
Time period	–	9–11 April 2010, 15–18 April 2013	–		–	
Camera trapping						
No. of tunnels	–		–	2	–	4
No. of nights	–		–	32	–	7–11[a]
Time period	–		–	1 April–3 May 2015	–	5–23 April 2016

a: Differed between tunnels; see table 4.

Table 3. Estimated number of amphibians killed per night along the studied road sections before and after mitigation, separated between mitigated and adjacent non-mitigated sections. Data were standardised to allow comparisons within and among sites; see text for further explanation.

Site 1. Skårby			
Section	Before	After	Δ
Mitigated	228	10	-218
Non-mitigated	91	60	-31
Total	*319*	*70*	*-249*
Site 2. Kyrksjölöten			
Section	Before	After	Δ
Mitigated	32.1	2.8	-29.3
Non-mitigated	10	47.4	+37.4
Total	*42.1*	*50.2*	*+8.1*
Site 3. Skeppdalsström			
Section	Before	After	Δ
Mitigated	25.2	0	-25.2
Non-mitigated	10.3	9.8	-0.5
Total	*35.5*	*9.8*	*-25.7*

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.27530v1 | CC BY 4.0 Open Access | rec: 11 Feb 2019, publ: 11 Feb 2019

Table 4. Number of amphibian recordings in the tunnels, and the net number passing through per night or 24h-period. For site 2–3 (cameras) data are separated between animals moving into the tunnel (i.e. in direction toward the breeding wetland) and those moving out (direction from the wetland). At site 1 (traps), only animals moving toward the wetland could be counted, as net traps blocked the tunnels in the other direction. Tunnels that were not monitored are indicated by lack of data.

Site 1. Skårby (only newts, 5 nights during peak migration period)					
Tunnel no.	S newt	GC newt	Both sp.		Net no./night
1	555	145	700		140.0
2	–	–	–		–
3	21	28	49		9.8
4	612	90	702		140.4
5	111	5	116		23.2
Sum	*1299*	*268*	*1567*		*313.4*
Site 2. Kyrksjölöten (only common toad, 14 significant migration days)					
Tunnel no.	In	Out	Net no.	In+out/24h	Net no./24h
1	871	389	482	90.0	34.4
2	544	214	330	54.1	23.6
Sum	*1415*	*603*	*812*	*144.1*	*58.8*
Site 3. Skeppdalsström (all amphibians, 7-11 days during peak migration period)					
Tunnel no.	In	Out	Net no.	In+out/24h	Net no./24h
1 (9 days)	41	17	24	6.4	2.7
2 (11 days)	258	254	4	46.5	0.4
3 (7 days)	70	38	32	15.4	4.6
4 (7 days)	20	0	20	2.9	2.9
5	–	–	–	–	–
Sum	*389*	*309*	*80*	*71.2*	*10.5*

Table 5. Estimated number of amphibians successfully crossing the road per night along the studied road sections before and after mitigation, separated between mitigated and adjacent non-mitigated sections. Data were standardised to allow comparisons within and among sites; see text for further explanation.

Site 1. Skårby			
Section	Before	After	Δ
Mitigated	139.1	319.5 [a]	+180.4
Non-mitigated	55.5	36.6	-18.9
Total	*194.6*	*356.1*	*+161.5*
Site 2. Kyrksjölöten			
Section	Before	After	Δ
Mitigated	13.8	60.1 [a]	+47.1
Non-mitigated	4.3	19.4	+15.1
Total	*18.1*	*80.4*	*+62.3*
Site 3. Skeppdalsström			
Section	Before	After	Δ
Mitigated	8.4	10.5 [a]	+2.1
Non-mitigated	3.4	3.3	-0.1
Total	*11.8*	*13.7*	*+1.9*

a: Including the number passing through tunnels; see table 4.

Figures

Figure 1: Overview of the three study sites in Stockholms larger metropolitan area. Map image credit: Lantmäteriet.

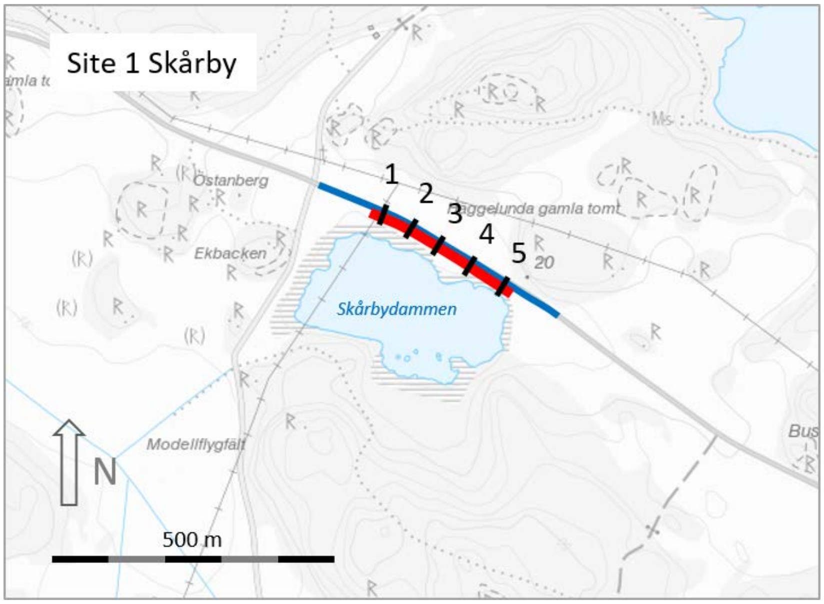

Figure 2: Map of Skårby (site 1) and the wetland Skårbydammen. Red line denote mitigated (fenced) section, black lines are the tunnels, and blue line is the road section where amphibians were counted before and after mitigation. Map image credit: Lantmäteriet.

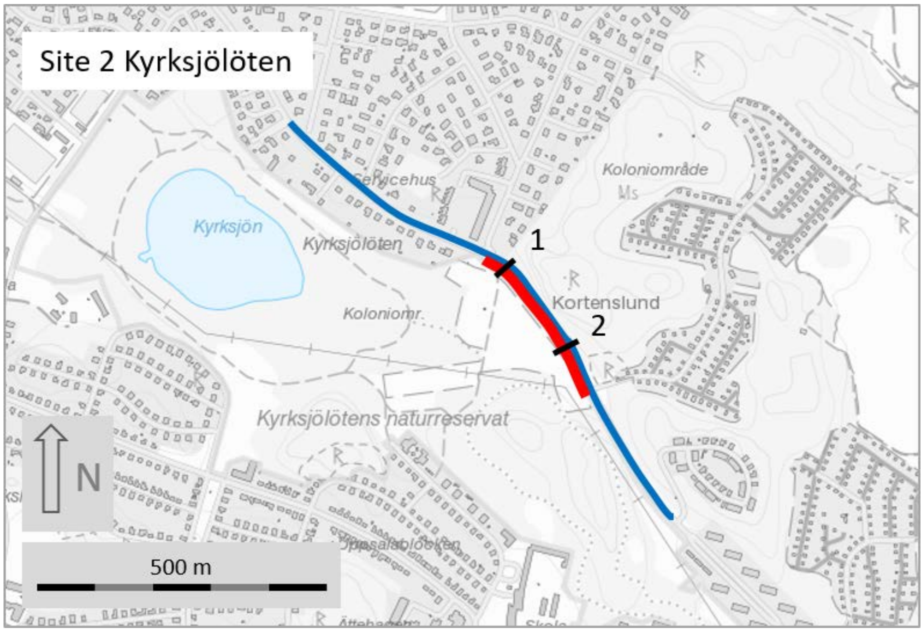

Figure 3: Map of Kyrksjölöten (site 2) and lake Kyrksjön. Red line denote mitigated (fenced) section, black lines are the tunnels, and blue line is the road section where amphibians were counted before and after mitigation. Map image credit: Lantmäteriet.

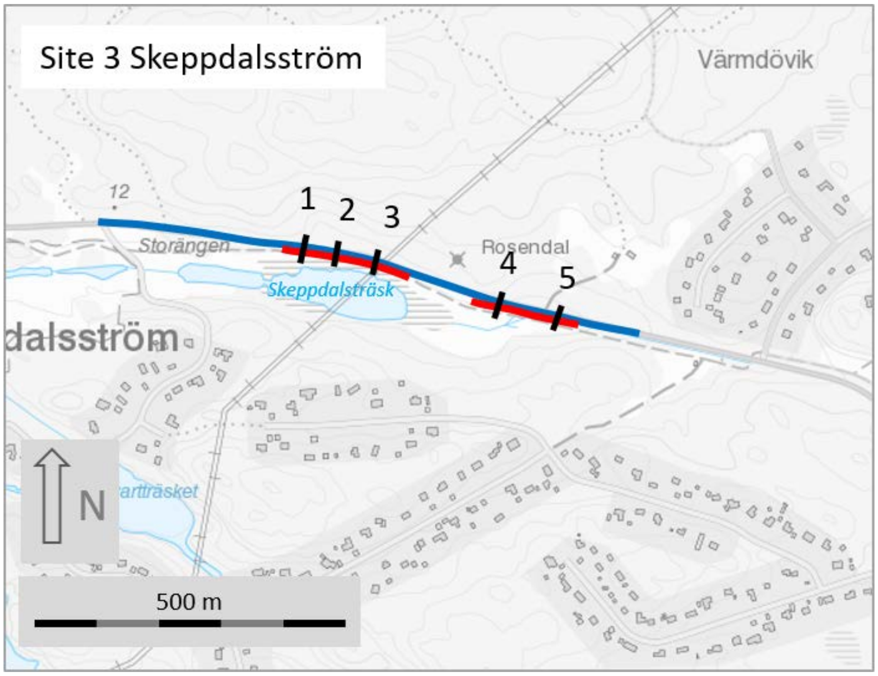

Figure 4: Map of Skeppdalsström (site 3) and the wetland Skeppdalsträsk. Red line denote mitigated (fenced) section, black lines are the tunnels, and blue line is the road section where amphibians were counted before and after mitigation. Map image credit: Lantmäteriet.

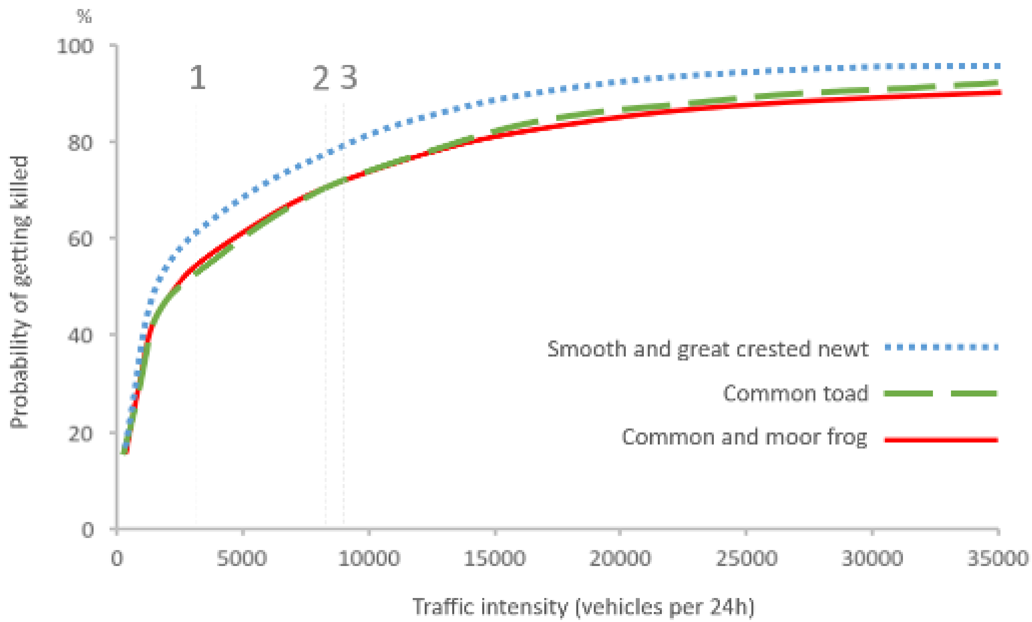

Figure 5. Probability of getting killed for an individual of different amphibian species at different traffic intensities, as described by Hels & Buchwald (2001). The probability of getting killed is weighted by amphibian behaviour (velocity and diurnal activity) and diurnal variation in traffic intensity, and assuming that amphibians are crossing perpendicular to the road. Traffic intensity of the three study sites are indicated by vertical dashed lines.

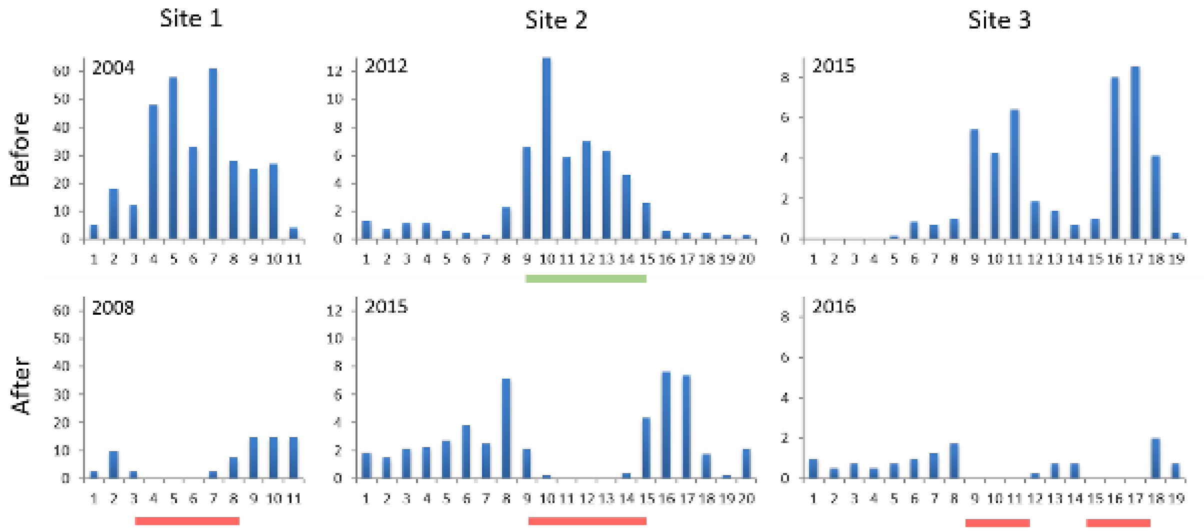

Figure 6. The number of amphibians found along the studied road sections, divided per evening/night and 50m road interval starting from northwest. Upper graphs are before mitigation, lower graphs are with mitigation in place. Site 1: Number of dead newts (smooth + great crested) found per night; Site 2: Number of live and dead common toads found per night; Site 3: Number of live and dead amphibians (four species) found per evening. Red lines denote mitigated sections (permanent amphibian fencing), green line at site 2 denotes temporary fenced section. Due to the difference in method, the data from counts along the temporary fence at site 2 cannot be directly compared to the other data.