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SafeBatPaths

Fumbling in the dark – effectiveness of bat mitigation measures on roads

Effectiveness of mitigating measures for bats – a review

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Executive summary

Transport infrastructures may have detrimental effects on bat populations. Bats are affected directly by vehicle collisions, light and noise disturbance, roost site destruction, habitat loss and degradation, and indirectly by fragmentation of their populations and habitats. In order to develop more ecologically sustainable infrastructures, road authorities implement mitigation and compensation measures for bats when upgrading or constructing new road schemes.

A variety of measures has been implemented to mitigate and compensate the adverse effects of roads and traffic on bats. Bats have been observed using most of the currently advised mitigation measures as intended, but the bats' behaviour and use of the measures have rarely been studied adequately to assess their effectiveness. A few recent studies with a robust study design have shown that some mitigation measures are effective, while only a minor proportion of bats used other measures to cross the roads safely.
Furthermore, the effectiveness of similar mitigation types differs significantly between species and sites. Because of the limited knowledge on the effectiveness of the presently advised interventions, the road authorities may have spent resources on potentially ineffective mitigation schemes.

To evaluate the effectiveness of road mitigation for bats, we reviewed studies on mitigation and compensation measures. We extracted information from scientific papers, consultancy notes, industry reports, student reports and conference presentations. The quality of the evidence of effectiveness was assessed from the study design. Replicated, randomized, controlled and before-and-after studies were assessed to provide the best evidence. Studies that only reported the use of a measure by bats were included in the review to present the available information on bats and road mitigation. A passage was characterised as effective if at least 90% of bats used the structure to cross the road safely.

Only a relatively low number of studies have been published on the effectiveness of mitigation measures on roads. The majority of the studies only described bats' use of the measures and did not report what proportion of bats did not use the measure. Nor did they compare the number of bats crossings at a site before and after the road was constructed. Many studies examined more than one type of mitigation measure but often only included a few replicates of each type.

Bats show large species-specific differences in echolocation, flight behaviour and typical flight height in relation to vegetation, vertical structures and landscape elements. Consequently, the effectiveness of mitigation measures varies between functional groups of bats, e.g. underpasses can be effective for low-flying species, but not for species that commute and forage in the open airspace. Therefore, it is essential for road developers to obtain detailed information on which bat species occur in the project area for a road. Such basic knowledge is crucial to make informed decisions and implement the most effective mitigation schemes.

Based on the evidence of bats' use of the mitigation measures and their effectiveness presented in the reviewed literature, we have assessed the measures' potential to mitigate impacts of roads (table 1).

Table 1. Assessment of measures and their potential effectiveness to mitigate road impacts on bats for low- and high-flying species (see Tab. 2). Y/N' denotes that studies have shown ambiguous results. A question mark indicates than no information on the use or effectiveness is available. Brackets indicate that some studies have indicated the measure is used or effective, but too few studies with a flawed design to be conclusive.

1/ A recommendable intervention if located and constructed correctly. Good evidence that bats use the structure or that the method is effective.
2/ A potential effective intervention which shows encouraging results. Further assessment requires better documentation of effectiveness or development of the measure.
3/ An intervention where more research is needed to assess its potential. Studies indicate some use and effectiveness for some species.
4/ An intervention that has proved to be ineffective, has shown very ambiguous results, or cannot be used for ecological mitigation. Not recommendable.

Mitigation method		Use (Y/N)*	Effective (Y/N)*	Assessment: In or near vegetation and surfaces	Assessment: Open-airspace
Fauna passages					
Wildlife overpasses		Y	Y	1	1
Modified bridges	Green verges	Y	(Y)	1	1
	Panels	Y	?	3	n/a
Bat gantries	Open structures	Limited	N	4	4
	Closed structures	Y	?	3	3
Hop-overs		Y	?/N	3	3*
Viaducts & river bridges		Y	Y	1	2
Tunnels & Culverts		Y	Y/?	2**	4
Other interventions					
Hedgerows & tree lines		Y	?	2	3
Barriers		Y	(Y)	2	3
Artificial lighting	Deterrence of bats	Y	?	3	3
	Adaptation of light spectrum	(Y)	?	3	3
	Restriction of light spill	(Y)	?	2	2
Audible warning		(Y)	?	3	3
Speed reduction		?	?	3	3
Ecological mitigation					
Bat boxes		Y	N	4	4
Bat houses		Y	Y/N	2	2
Relocate tree trunks		(Y)	Y/N	3	3
Artificial holes in trees		?	?	3	3
Tree retention		?	?	2	2
Habitat improvements		Y	?	2	2

'*On low bridges and roads on embankments over tunnels and culverts. **Effectiveness also size-dependent for low-flying species.

Further details on the documentation of use and effectiveness, the advantages, constraints and uncertainties in the assessments for each of the different mitigation types is presented and discussed in the report.

Only a few measures were assessed as effective and recommendable providing that they are designed and located optimally. For most of the measures there is little evidence suggesting that they are effective. These measures should be regarded as experimental interventions. If such unverified measures are implemented, they should be studied methodically to determine their effectiveness. Potentially, in situ field experiments could be performed before the construction of the road to optimize the mitigation location and design details of the structure. A robust, quantitative scientific approach appropriate for statistical analysis is advised for these evaluations.

Generally, fauna passages should be located on existing commuting routes to ensure high usage, and the structures should be constructed to allow the bats to cross the road without changing flight height or direction. Furthermore, the mitigation structures should be well-connected by hedgerows and trees to the landscape elements used by bats as commuting routes. Attempts to divert bats away from established commuting routes to safe crossing sites show ambiguous results.

The mitigation measures should be in place well in advance - preferably some years - before the road opens to traffic to allow the bats to habituate to the measures. Some of the measures may take years before they become effective, e.g. trees and shrubs connecting the passages to adjacent key habitats. Bats adapt to long-term changes in the landscape, but if the immediate effects of a road have not been sufficiently mitigated when the road opens to traffic, there is a risk that the populations can be critically depleted or lost before the long-term mitigation measures become effective.

As a consequence of the shortage of well-designed studies on the effectiveness of bat mitigation and compensation measures, little can be concluded on the effectiveness of most interventions. Thus, it is difficult to assess the cost-effectiveness of bat mitigation schemes. To change this situation and to develop better mitigation strategies for bats, more robust studies of the effectiveness of mitigations is needed.

It is a complex task to estimate which traffic-related mortality rates and fragmentation levels the bat populations can sustain, and to define universal criteria for the effectiveness of mitigation structures. The application of population and landscape modelling to predict the probable effects of roads and mitigation measures on bat populations is hampered by a general lack of quantitative data on demographic rates, population dynamics and road impact. Consequently, to comply with the conservation concerns for bats, a precautionary approach should be applied when assessing the effects of roads and the effectiveness of bat mitigation measures.

1 Introduction

Transport infrastructures can have negative impacts on wildlife populations and the environment (Forman & Alexander 1998, van der Ree et al. 2015). Correspondingly, transport infrastructure may have detrimental impacts on bats and their population status.

Roads and traffic may affect bats directly through increased mortality, destruction of roost sites and foraging habitats, light and noise disturbance, and indirectly by fragmenting the populations and their habitats (e.g. Russell et al. 2009, Abbott et al. 2015, Fensome & Mathews 2016). The life history of bats and their ecology make them highly vulnerable to increased mortality and environmental changes induced by humans. Bats have relatively long life expectancies, and low reproductive rates (Sendor & Simon 2003, Altringham 2011, Chauvenet et al. 2014). Therefore, increased mortality rates and lowered reproductive success may have a severe negative effect on the population status of bats (Schorcht et al. 2009, López-Roig & Serra-Cobo 2014).

Habitat loss, degradation and fragmentation may also divide the populations into smaller fractions and make them increasingly vulnerable to catastrophic stochastic events. Bats require large home ranges and utilise much more widely dispersed resources compared to other mammals of similar sizes (Robinson & Stebbings 1997, Encarnação et al. 2010, Altringham 2011). Bats may commute several kilometres on a nightly basis between roosting sites and several important foraging habitats, and during autumn and spring bats migrate long distances between summer habitats and winter hibernation sites (Hutterer et al. 2008).

The impact of roads on bat populations varies between bat species due to their different feeding ecology and flight patterns. Low flying, structure-bound bat species in particular are at risk of being killed when crossing roads, e.g. *Myotis, Plecotus* and *Rhinolophus* species (Baagøe 1987, Fensome & Mathews 2016). However, high mortality rates have also been recorded locally for other bats which normally fly higher above traffic height, e.g. *Nyctalus* species in forested areas where commuting routes are severed by the road (Lesiński et al. 2011).

A number of methods have been described and implemented in Europe to protect bats and reduce the negative effects of roads on the populations (e.g. Limpens et al. 2005, National Road Authorities 2006, Nowicki et al. 2008, Brinkmann et al. 2012). These interventions include mitigation measures that aim to reduce road-related mortalities and maintain road permeability for the bats by guiding bats safely across the road, e.g. bat gantries, wildlife overpasses, tunnels. Other mitigation measures aim only to reduce mortality risk by preventing or deterring the bats from crossing the roads, or by guiding the bats to safer crossing points, e.g. artificial lights, barrier screens, and planting of hedgerows and trees. Habitat improvement and restoration projects designed out to compensate for habitat degradation and loss in order to maintain or improve the carrying capacity of the project area have also been suggested and implemented.

While these mitigation measures intuitively could reduce the impact of roads on bats, little evidence has been produced documenting that the current mitigation measures are actually effective (Berthinussen et al. 2013). Most knowledge on bats and road mitigation measures are based on anecdotic observations and descriptive studies that only address bats' use of the measures. Only a few recent studies have adequately tested the effectiveness of mitigation measures (Abbott et al. 2012a, 2012b, Berthinussen et al. 2012, Berthinussen & Altringham 2015, SWILD & NACHTaktiv 2007). These studies have shown that often only a minor proportion of the bats and bat species used the mitigation structures to cross the roads safely.

A mitigation structure may only reduce the mortality risk and the barrier effect of the roads sufficiently if it is used by a large proportion of the bats, thus sustaining the affected bat populations. As a consequence of the insufficient knowledge on the effectiveness of the various bat mitigation techniques, European road agencies may currently be implementing mitigation measures which are ineffective and insufficient to protect and maintain viable bat populations.

Guidelines on bat mitigation measures on roads have been published in many countries (Highway Agency 2001, 2006, Limpens et al. 2005, National Road Authorities 2006, Brinkmann et al. 2008, 2012, Nowicki et al. 2008, 2016, Møller & Baagøe 2011). The accumulation of experience within each country is slow as few mitigation projects are monitored. Cost-effective mitigation strategies for bats on roads can better be achieved if the knowledge and experiences accumulated in several countries are combined.

The objectives of the present report were to: 1/ review studies on bats and road mitigation measures to evaluate the documentation for their use by bats and assess the effectiveness of the different mitigation measures, and 2/ to recommend mitigation measures if applicable, and outline the lack of knowledge and documentation of the effectiveness of the different types of mitigation measures. We sought to include grey literature in the form of unpublished consultancy reports, industry reports and student reports in the review to present the level and quality of all available information on bat mitigation measures.

2 Methods

2.1.1 Literature search

Relevant literature and documention on bat mitigation measures were identified by searching online literature databases and reference catalogues: Web of Science and Scopus citation index, ResearchGate and Google Scholar. The search was undertaken using a combination of the following keywords related to bats and road infrastructure: “bat and mitigation”, “road”, “highway”, “street”, “traffic”, “fauna passage”, “green bridge”, “environmental bridge”, “landscape bridge”, “wildlife overpass”, “gantry”, “underpass”, “road bridge”, “road tunnel”, “culvert”, “streetlight”, “light pollution”, “noise”, “road mitigation”, or “railway”. We also searched the internet for similar keywords and combinations in the major European languages.

We placed a great effort in searching for the “grey literature”, e.g. consultancy reports, industry reports, and student reports by explicitly requesting these from bat and road experts. Grey literature rarely appears on literature databases and it is rarely available on the internet. As a result, it is often overlooked.

Furthermore, proceedings of the Infra Eco Network Europe (IENE) conferences, the International Conference on Ecology and Transportation (ICOET) and bat conferences were scanned for relevant literature on bats and transport infrastructures.

Reference lists in these abstracts, papers and reports were scanned to identify further relevant papers and reports.

The review focused on studies of bat mitigation measures on roads, but studies on railways were also included. Studies on bats and mitigation in relation to railways are rare. The effects of railway infrastructure on bats are assumed comparable to the effects observed from road infrastructure.

The present review and evaluation of bat mitigation measures focuses on European studies and studies of European species. Major studies from other continents are included, e.g. studies of bats in bridges conducted in North America.

2.1.2 Summaries and assessments

We scanned the literature and extracted the relevant information on the mitigation measures, study design and results from each study. This information is presented in the report as summaries of each individual study organised in chapters for each type of mitigation measures. The studies are presented chronologically starting with the most recent. Some studies described the use or effectiveness of several types of measures. The summaries of these studies are included in all relevant chapters, but the presented results may differ to focus on the results of the specific measures.

Following the presentation of the summaries of studies on each mitigation type, we assess the evidence of use or effectiveness of the measure and recommend the measure if appropriate or applicable. Recommendations for future research to provide better evidence or enhance the effectiveness of different mitigation measures are outlined based on our review of the studies. In the assessment section for the specific mitigation measures we may provide information and incidental observations from non-summarised literature if the information is relevant for the interpretation of the evidence of effectiveness and assessment of the measure.

Artificial roost sites, particularly bat boxes bat houses, and roosting sites in bridges, are widely used as conservation interventions to mitigate many threats, including construction of transport infrastructures. There is a huge quantity of primarily grey literature on the use of artificial roosts as compensation for roost site destruction. Most of these descriptive studies were not related to road or railway infrastructures; the majority simply focused on bats' use of different bat box designs. We did not review all literature on artificial roost sites, but focused on studies where bat boxes, bat houses, etc. had been implemented to mitigate the detrimental effects of roads or railways. General information provided in recent reviews of artificial roost sites is included in the assessments and recommendations of these mitigation measures. Examples of artificial roosts implemented in conservation projects unrelated to roads and railways mitigation are provided only if they are relevant for the assessment of the effectiveness of the measure.

2.2 Evaluation criteria

To assess the evidence for effectiveness provided by the reviewed literature, the results and conclusions of each study were evaluated according to a set of criteria (Table 1).

Replicated, randomized, controlled studies with paired sites and before-and-after monitoring provide the best evidence of an effect. Whenever possible, evidence of the effects of mitigation measures or management interventions should be supported by statistical tests.

Study design, sample size, metric and reported effects of the tested measures in each study are outlined in the summaries to make our assessment of each study transparent to the readers.

We included studies that did not examine or provide evidence of the effectiveness of a measure but merely reported on bats' use of a measure in order to present the existing level and quality of evidence and knowledge on bats and road mitigation measures.

2.3 Definitions

2.3.1 Effectiveness of mitigation measures

We follow the definition by Berthinussen & Altringham (2015) and characterise a mitigation measure as effective only if at least 90% of bats use the structure to cross the road safely without risk of traffic collision. Furthermore, for a mitigation structure to be effective to maintain landscape connectivity, the number of bats crossing the road at the mitigated commuting route should not be substantially lower after the road is constructed than before. This parameter was rarely reported. Hence, it was excluded in the evaluation of the effectiveness of the mitigation measures.

Table 1 Assessment criteria (adapted from Berthinussen et al. 2013. www.conservationevidence.com).

Criteria	Meaning
Experimental	The effects of mitigation or compensation measures on bats behaviour at a road construction is examined with an experimental set-up.
Before-and-after	The effect of mitigation or compensation measures is documented in the study by comparing bats behaviour before and after the measure was introduced at a site.
Controlled	The effect of mitigation or compensation measure is assessed by comparing simultaneous studies of bat behaviour at the mitigation structure and at an unmitigated control site. E.g. measures of bat activity in an underpass compared to activity of bat crossing above the road, or activity of bats crossing the road adjacent to the underpass.
Replicated	Bat behaviour is studied simultaneously at more than one site with similar types of mitigation or compensation measure. Number of replicates / study sites is provided.
Paired sites	Study sites are considered in pairs comprising a mitigated site and an unmitigated site. This makes it easier to detect an effect of the mitigating or compensating measure. The paired sites must have similar environmental conditions or habitat composition adjacent to the road.
Site comparison	A study that considers the effects of mitigation or compensation measures by comparing sites with different types of measures, or measures of different age.
Randomized	Effects of mitigation or compensation measures are examined at mitigated sites that have been randomly allocated along a road. This means that biases in the outcome of the measures due to differences in initial conditions at the sites are less likely to occur.
Population	A study that has evaluated the effectiveness of mitigation or compensation measures on the status of affected bat populations.
Descriptive	A study describing the behaviour of bats at a site with a supposed mitigating measure or intervention in quantitative terms, but presents no statistical analysis of the results.
Meta-study	Information on effectiveness of measures based on a systematic review of systematic studies and formal meta-data-analysis. The strength of evidence they offer will be evaluated based on the number of included studies, the size of each study and the design of the meta-analysis.
Review	Information of studies on usage or effectiveness of measures extracted from reviews. Such information is only presented when the original study has not been available for reviewing.

For a bat to cross a road safely, it must either pass under the road via an underpass or over the road above traffic height. Safe height is defined here as 5 m or higher. Lorries are normally up to 4 m high but higher vehicles are allowed in some countries, and given their small size, bats may easily get caught in the slipstream from passing vehicles (Stratmann 2006). For the mitigation scheme to be effective, the bat populations affected by the road must be maintained during and after construction, and the road must not constitute a barrier for the bats. Bat box schemes or other artificial roosts must be able to maintain colony size to be effective.

A high usage rate of mitigation measures must be attained to reduce vehicle-collision risks for bats and maintain connectivity between habitats in the landscape sufficiently to preserve viable bat populations. All bat species have long life spans and very low reproductive rates, and their population status is highly sensitive to increased mortality rates (Altringham 2011, Chauvenet et al. 2014, Lopez-Roig 2014). Annual adult survival rates in two common European bat species is between 70-90% (Sendor & Simon 2003, Schorcht et al. 2009). The level of effectiveness of a mitigation measure, which is required to reduce mortality risks sufficiently to protect the status of bat populations, probably varies between species, and will depend on population status, habitat use, human land use, as well as road traffic intensity.

On roads with a low traffic intensity and hence a lower probability of vehicle-collisions per bat road crossing, a usage rate lower than 90% may be sustainable for a bat population. A lower effectiveness of the mitigation measures and a larger mortality rate for local populations in the vicinity of roads might also be sustainable for common species with large regional populations that can act as potential source populations. For rare species, species with patchy distribution or small, vulnerable populations, the 90% usage rate may not reduce collision risk sufficiently to protect the status of the bat populations. However, the application of predictive population and landscape modelling to predict the effects of road schemes and mitigation strategies on bat populations explicitly, is hampered by a general lack of data on demographic rates and population dynamics on bats. Therefore, to comply with the conservation concerns for bats in Europe, a precautionary approach must be applied when assessing the effects of roads and the effectiveness of bat mitigation measures.

2.3.2 Bat manoeuvrability and flight heights

Bats' flight behaviour, manoeuvrability and typical flight height when commuting in open areas vary considerably between species. Bat species show differences in flight behaviour in relation to vertical structures such as vegetation (clutter), clifss, walls, etc. and show adaptations to such different behaviours both in wing morphology (Baagøe 1987 and unpubl., Norberg & Rainer 1987) and in echolocation calls (Neuweiler 2000, Schnitzler & Kalko 2001).

These differences imply that the different bat species are not equally at risk of collisions with vehicles when commuting across roads or when foraging over roads or along vegetation on road verges.

The larger, more narrow-winged and less manoeuvrable species often fly high and in the free airspace away from clutter (vegetation) or manmade structures. However, under certain conditions, even these species will fly lower e.g. when hunting insects in completely open areas or flying near roost sites. Other species are more manoeuvrable and most often fly near and along vegetation and other vertical objects, but also spend much time in the free air space. A few of these species are also adapted to hunt in extremely low flight over water surfaces. When foraging along hedgerows and forest edges parallel to roads these species may be at risk of collisions.

A third group of bat species have low wing aspect-ratio and are extremely manoeuvrable. They prefer to hunt and commute within or close to vegetation or vertical objects. Flying close to the vegetation may also reduce predation risk. It is among the groups of manoeuvrable bats that we find species that, *when commuting*, often follow linear or other longitudinal elements in the landscape, e.g. hedgerows, stone walls, embankments, forest edges, and streams (Limpens & Kapteyn 1991, Dietz et al. 2009). These clutter-adapted bats follow such landscape elements at variable flight heights, but when the bats have to cross a wide, open stretch many of them tend to fly low over the ground, (see e.g. Møller & Baagøe 2011). Some of the species fly very low e.g. *Myotis bechsteinii* and *Rhinolophus hipposideros* (Baagøe 2001, SWILD & NACHTaktiv 2007). This behaviour puts them at a greater risk of colliding with traffic on roads. Some of the species are also very manoeuvrable and can change flight direction or flight height extremely quickly, whereas others are less so.

In order for the reader to assess 1) the risk of each species being victims of car collisions, and 2) which bat species a certain measure could be relevant for, we have tentatively categorized some of the European bat species according to their flight height and manoeuvrability when commuting in open areas. The categories are based on our own experiences, as well as information from various authors. Estimates of manoeuvrability are based on a careful assessment of how different bat species react to vertical obstacles erected across their commuting route.

It must be stressed that bat species shows a large natural behavioural plasticity and may react unpredictably to alterations in the landscape. Appropriate consideration to this behavioural plasticity is much too often neglected. The tentative categorisation below according to general flight behaviour merely attempt to point out what the different species will ***most often*** do. Because of the bats' flexible behaviour, in situ observations are recommended well in advance of road construction where commuting routes are severed and mitigation measures are planned and before the opening of a road to traffic.

Provitional categories of bat species

A. Extremely manoeuvrable bats, which often fly within foliage, or close to vegetation, surfaces and structures at variable flight heights. When commuting, they often follow linear and longitudinal landscape elements. Low-flying (typically < 2.0 m) when commuting over open gaps.

B. Very manoeuvrable bats that most often fly near vegetation, walls, etc. at variable heights but occasionally hunt within the foliage. When commuting, they often follow linear and longitudinal landscape elements. Flying at low to medium height when commuting over open gaps (typically < 5 m).

C. Bats with medium manoeuvrability. They often hunt and commute along vegetation or structures at variable heights, but rarely close to or within the vegetation. May also hunt in open areas. Commuting over open stretches generally takes place at low to medium heights (typically 2 – 10 m) with no clear tendency to lower flight.

D. Bats with medium manoeuvrability with a more straight flight pattern than bats in category C. They hunt and commute both in the away from vegetation and structures in a variety of flight heights. May occasionally fly but never hunt within vegetation. Commuting over open stretches tend to occur at medium heights (2 – 10 m) with no clear tendency to lower flight.

E. Less manoeuvrable bats that most often fly high and in the open airspace away from vegetation and other structures. These bats generally commute over open stretches at medium heights or higher (10 m and often higher). It must be stressed that even these species may fly quite low over open areas under certain conditions, e.g. when hunting insects over warm (road) surfaces, or when they emerge from a roost site.

Table 2. Provisional categorisation of European bat species to functional groups based on their typical flight behaviour and height. Brackets indicate that the knowledge on the species' flight behaviour is limited.

		In or near vegetation and surfaces			Open airspace	
Latin name	**Common name**	**A**	**B**	**C**	**D**	**E**
Rousettus aegyptiacus	Egyptian fruit bat				(X)	
Rhinolophus hipposideros	Lesser horseshoe bat	X				
Rhinolophus ferrumequinum	Greater horseshoe bat		X			
Rhinolophus euryale	Mediterranean horseshoe bat		X			
Rhinolophus mehelyi	Mehely's horseshoe bat		X			
Rhinolophus blasii	Blasius's horseshoe bat		(X)			
Myotis daubentonii	Daubenton's bat		X			
Myotis dasycneme	Pond bat			X		
Myotis capaccinii	Long-fingered bat			X		
Myotis brandtii	Brandt's bat		X			
Myotis mystacinus	Whiskered bat		X			
Myotis aurascens	Steppe whiskered bat		(X)			
Myotis alcathoe	Alcathoe bat		X			
Myotis nipalensis	Asiatic Whiskered bat		(X)			
Myotis nattereri	Natterer's bat	X				
Myotis escalerai	Iberian Natterer's bat	X				
Myotis emarginatus	Geoffroy's bat	X				
Myotis bechsteinii	Bechstein's bat	X				
Myotis myotis	Greater mouse-eared bat			X		
Myotis blythii	Lesser mouse-eared bat			X		
Myotis punicus	Maghreb Mouse-eared bat			(X)		
Nyctalus noctula	Common noctule					X
Nyctalus lasiopterus	Greater noctule					X
Nyctalus leisleri	Leisler's bat					X
Nyctalus azoreum	Azores noctule					(X)
Pipistrellus pipistrellus	Common pipistrelle			X		
Pipistrellus pygmaeus	Soprano pipistrelle			X		
Pipistrellus hanaki	Hanak's Pipistrelle			(X)		
Pipistrellus nathusii	Nathusius's pipistrelle			X		
Pipistrellus kuhlii	Kuhl's pipistrelle			X		
Pipistrellus maderensis	Madeira pipistrelle			(X)		
Hypsugo savii	Savi's pipistrelle				X	
Vespertilio murinus	Parti-coloured bat					X
Eptesicus serotinus	Serotine				X	
Eptesicus nilssonii	Northern bat				X	
Eptesicus isabellinus	Isabelline serotine				X	
Eptesicus bottae	Botta's serotine				X	
Barbastella barbastellus	Barbastelle				X	
Plecotus auritus	Brown long-eared bat	X				
Plecotus macrobullaris	Alpine long-eared bat	X				
Plecotus sardus	Sardinian long-eared bat	(X)				
Plecotus austriacus	Grey long-eared bat	X				
Plecotus kolombatovici	Balkan long-eared bat	(X)				
Plecotus teneriffae	Canary long-eared bat	(X)				
Miniopterus schreibersii	Schreiber's bent-winged bat				X	
Tadarida teniotis	European free-tailed bat					X

3 Evaluations

3.1 *Overpasses*

Overpasses are intended to help bats to fly over the road at safe height above the traffic. Four different types of overpasses purposely build as bat mitigation measures are described in literature: bat gantries, hop-overs, wildlife overpasses (including landscape bridges), and modified overbridges for minor roads which have been fitted with adaptations for bats (e.g. Iuell et al. 2003, Nowicki et al. 2008, Møller & Baagøe 2011,). Bats may also use technical road structures build for other purposes than bat crossings, e.g. overbridges for minor roads, pedestrian bridges and road sign gantries.

3.1.1 Bat gantries

Bat gantries are simple, narrow, linear, bridge-like structures constructed specifically for bats to guide them over the road at safe height (e.g. Highway Agency 2006, Møller & Baagøe 2011). The gantry structure spans across the road above traffic height and is intended to provide the bats with sufficient echo that they do not decrease their flight height when crossing the road. The design of bat gantries ranges from steel wire gantries with spheres, steel mesh and lattice metal structures to solid constructions resembling narrow bridges (e.g. Berthinussen & Altringham 2012, Berthinussen & Altringham 2015, Schut et al. 2013, Cichocki 2015, Nowicki et al. 2016).

Summaries

Bats use of three wire gantries and a road overbridge in the United Kingdom was examined in a replicated, site comparative study by Berthinussen & Altringham (2015). The gantries had been constructed to mitigate adverse effects on bats at a dual carriageway. The road passes through woodlands and farmlands. The three gantries (one of them not yet fully completed when studied) were each surveyed 4-9 times at dusk or dawn. Surveys were conducted by means of automatic ultrasound recorders combined with visual observations from observers stationed at each side of the road at the gantries. Flight height, direction, proximity to the gantry and time of crossing were recorded for each bat. Bat activity was very low (or absent) at all three bat wire gantries, and none of them were effective in guiding bats safely over the road. At the gantry with the highest activity, 80% of bats (*Pipistrellus pipistrellus*, *Pipistrellus pygmaeus*, and a single *Plecotus auritus* and *Nyctalus/Eptesicus*) crossed the road at risk of collisions with traffic and only two bats (*Nyctalus/Eptesicus*) of the 35 that crossed could be considered to be using the gantry. None of the five bats observed at the other complete wire gantries used the structures to cross the road, and nearly all bats crossed at unsafe heights. At the uncomplete gantry only two bats were registered. One of those would have been considered using the gantry if the wires had been in place; the other one crossed at unsafe height.

In a replicated, controlled, site comparative study Cichocki and co-workers (Cichocki 2015) monitored bat activity at three gantries constructed as lattice steel structures. The gantries were constructed to facilitate safe bat crossings at a motorway in agricultural and forested landscape in Poland. One of the aims of the gantries was to protect the bats migrating to and from a nearby large hibernaculum. Bats were also monitored at underpasses for large mammals and watercourses, wildlife overpasses constructed for large mammals, and at road underpasses and overbridges on the motorway. Screens were erected on the road verges above all culverts and at one of the gantries. Bat activity was recorded once a week in March-November from 2012 to 2014 near the gantries and along 250 m road sections on

each side of the gantries from sunset to sunrise using ultrasound detectors, infrared cameras and visual observation. Simultaneously, road-kills were recorded every week to identify potential conflict sites.
The preliminary results suggest bat activity at the gantries were not larger than at road sections next to the gantries. *Nyctalus noctula* and *Pipistrellus* sp. were the most common species at the gantries. *Barbastella barbastellus* and *Eptesicus serotinus* were recorded sporadically. These bats frequently flew along the forest edges and glades near the road, and especially the *Nyctalus noctula* bats were feeding along and over the road. Only very few *Myotis* sp. were observed at the gantries. The bats tended to use the existing flight routes ignoring the constructions. Flight routes across the motorway were ill-defined in the forest surrounding the gantries and bats activity was 'concentrated' in 50-100 m wide zones (J. Cichocki, pers. comm.). Only a few fatalities were recorded (n=25). Most of these were *Nyctalus* and *Pipistrellus* bats.

A replicated, site comparative study, Naturalia Environnement & FRAPNA (2015, 2016) monitored bat activity near two bat gantries, a ramp which could function as a hop-over, two large tunnels constructed for large mammals and two large culverts at a motorway (A89) in France to assess the use and effectiveness of the mitigation measures. The motorway traverses a forested mosaic landscape of national interest for bats. Close to the motorwayis a very important hibernation site for *Barbastella barbastellus*. Bat activity was recorded acoustically for seven nights in each month from May to October in 2014 and 2015. Flight patterns were also monitored with a thermographic camera for three nights at the gantries and the ramp in May, July/August and September in 2014 and 2015.
Bat activity near the gantries was relatively high and dominated by *Pipistrellus* sp. (2014: 83%, 2015: 88%), *Barbastella barbastellus* (2014: 6%, 2015: 8%), *Myotis* sp. (2014: 5%, 2015: 2%) and 'Serotules' (*Nyctalus* sp., *Tadarida teniotis* and *Eptesicus serotinus*) (2014: 5%, 2015: 2%). For the bats observed with thermal camera at the gantries, 33% used the gantries to cross the motorway in 2014, while only 6% did in 2015. Some of the observed bats turned back and failed to cross the road, 1% in 2014 and 5% in 2015. 66% of the recorded bats in 2014 and 89% in 2015 did not use the gantries but were foraging or flying in transit along the motorway. Further studies of the bats' use of the mitigation measures are planned for the next years by Naturalia Environnement and FRAPNA Loire, the National Museum of Natural History of Paris, Greifswald University and Autoroutes du Sud de la France (VINCI Autoroutes).

A small, controlled study by Czerniak et al. (2013) observed bat flight patterns near a lattice steel gantry and a nearby unmitigated motorway section in Poland. The gantry was constructed two years prior to the study at a forest edge. *Myotis myotis* and *Barbastella barbastellus* had been observed commuting along the forest edge in the pre-construction survey. Bat flight patterns were monitored visually for two hours at dusk ten times during spring 2013. Significantly fewer bats crossed the motorway using the gantry at the forest edge (16 bats) than at a longer unmitigated section of the motorway inside the forest (103 bats) that served as control. The authors concluded that the gantry was valuable for bats as proportionally more bats per metre of road crossed at the gantry at the forest edge than at the unmitigated road section. However, the original flight corridors had been disrupted during forest clearance and road construction thus reducing the potential effectiveness of the gantry.

The use by bats of a recently built gantry across a main road was examined in a controlled study in the Netherlands (Schut et al. 2013). The gantry and 11 control sites were examined; the gantry for 4 nights using two ultrasound detectors. The detectors were placed at 5 m height on poles close to the gantry ends, one aimed upwards and one downwards with a sound screen between. At both sides of the road and gantry, a 400 m long transect was monitored using ultrasound detectors and visual observations. Observed species were *Pipistrellus pipistrellus* (n=122), *Eptesicus serotinus* (n=43) and a few *Myotis daubentonii*, *Nyctalus noctula*, and *Pipistrellus nathusii*. Species were pooled in the analysis of the results. 82% of documented passages at all studied sites occurred at safe height more than 5m above the road. The control locations were equally used and as safe as the gantry location. On average, there were 5.5 passages per night at the gantry, of which 72% was at a safe height, against 5.1 passages per location per night at the control locations, of which 69% at a safe height. The authors relate the lacking preference of the gantry to the fact that it was not placed on a bat commuting route.

A controlled, replicated site comparison study of the effectiveness of wire gantries, underpasses and unmitigated sites was carried out in the United Kingdom (Berthinussen & Altringham 2012a). Three underpasses and four bat gantries were investigated. The proximity to the gantry and the flight height of bats crossing the road at the sites was recorded. Data was compared to those from adjacent, road-severed commuting routes that had no crossing structure. Bats did not cross the road at bat gantries more than at the unmitigated road crossing sites, and the gantries did not effectively increase the height at which bats flew above the road. There was no evidence that bats were using gantries by flying in close proximity to them, as they do along hedgerows. One of the gantries had been in place for 9 years close to a known commuting route. The bats did not make even small changes to their flight paths to use gantries.

O'Connor & Green (2011) presented reviews of eight case studies where wire gantries (with either mesh or small plastic spheres) had been used as mitigation. Monitoring effort and length varied considerably, and definitions of bat usage of the gantries were in most cases unclear. However, according to the monitoring none of the gantries managed to guide more than 50% of bats across roads at safe height. Bat activity at most gantries was low. At one gantry, bats were observed crossing the road at the original commuting route along a bridleway inside the forest instead using the gantry which was placed at the forest edge. At another gantry, *Myotis*-bats were observed crossing low over the road within the traffic zone.

Temporary gantries

O'Connor & Green (2011) and Pouchelle (2016) have briefly reported bats' use of temporary gantries implemented during the construction phase of roads.

A temporary gantry consisting of two tensioned wires with polystyrene spheres placed at short intervals on the wires to increase detectability for the echolocating bats has been installed across a wide road cutting that fragmented a woodland corridor for bats in France (S. Roue, pers. comm., Pouchelle 2016). A wildlife overpass is to be constructed later at the site. A short descriptive survey using 3d-acoustic recording (two nights pre-construction and four nights post-construction) showed that bats did not cross the road transect before the wire gantry was installed. When installed *Pipistrellus* sp. and *Myotis myotis* used the wire gantry to cross the gap in the forest corridor (S. Roue, pers. comm., Pouchelle 2016).

Temporary gantries comprising three ropes with small plastic flags at intervals were installed following vegetation clearance and prior to road construction at sites where permanent bat gantries were to be installed on a dual carriageway in the United Kingdom (O'Connor & Green 2011). Bat activity was recorded acoustically over ten nights during May to September 2007 at a temporary gantry and at a walking transect along the road transect. No bats were recorded crossing the road development transect using the temporal bat gantries. Bats continued to fly and cross the road transect at the established commuting route 20 m from the temporary gantries.

Assessment and recommendations

We found seven studies aiming to evaluate the use or effectiveness of bat gantries, and two descriptions of bat behaviour near temporary gantries. None of the gantries in the studies could be classed as 'effective' as defined by Berthinussen & Altringham (2015) i.e. less than 90% of the bats made crossings at a safe height in these studies.

Only two studies measured how close the bats flew to the gantry in order to determine if bats were actually using the gantry or just crossing the road at the position of the gantry. Furthermore, some studies lacked information on flight height of the bats crossing the roads at the gantries. Due to these circumstances, it was not always possible to determine from the studies if a) the bats crossing the road at the gantry were actually using the gantry and b) whether bats crossing the road at the gantry were doing so at safe height.

Wire gantries were the most studied gantry design; 6 wire gantries of two different designs have been thoroughly tested in the United Kingdom (Berthinussen & Altringham 2012, 2015) with no evidence that bats used the gantries more than other unmitigated crossing points, or that gantries effectively increased the height at which bats flew above the road. One of the gantries was unsuccessful through 9 years. The bats did not make even small changes to their flight paths to use the gantries.

None of the studies provided evidence that any gantry design can effectively help bats cross roads safely. This measure does not seem promising and cannot be recommended at present. However, carefully designed research and controlled testing including studies of the behaviour of individual species would be needed to thoroughly evaluate the efficiency of bat gantries.

The specific design of the gantry could be of importance to its efficiency. Only wire gantries have been adequately studied with a robust scientific approach. This gantry type was consistently not used by bats. Other light constructions, e.g. steel mesh gantries and lattice structeres are probably also ineffective. More solid designs of gantries should be studied further. Such structures may provide bats with better echoes and also reduce noise and light disturbance from vehicles on the road below.

3.1.2 Hop-overs

A hop-over consists of existing or planted trees and shrubs on either side of a road (Limpens et al. 2005). The tall vegetation on the road verges is expected to encourage the bats to maintain or increase their flight height to cross the road at safe height above the traffic. The vegetation can be combined with earth ramps or vertical screens on the road margins. It is usually recommended for narrower roads, but it is suggested on wider roads that vertical structures be placed on the central reservation creating a "double" hop-over. Hop-overs can be erected on roads level with the surrounding terrain, roads in cuttings, as well as on bridges (Bach 2008, Bach & Bach 2008).

Summaries

The effectiveness of hop-overs was examined experimentally in a replicated, controlled study by comparing bat flight patterns and heights before and after two parallel screens were installed across an open gap in a commuting route (Christensen et al. 2016). The screens (4 m high and 20 m long) were installed to simulate a hop-over at a hedgerow severed by a road. The distance between screens was 8-10 m. Four experimental sites and a control site were studied using ultrasound detectors, infrared video and visual observations. The flight

patterns and heights were recorded two nights before, on the first night and up to four nights after screens were installed. A total of 1337 bat passes were recorded (952 *Myotis daubentonii*, 323 *Pipistrellus pygmaeus* and 62 *Barbastella barbastellus*).
The percentage of *Myotis daubentonii* and *Pipistrellus pygmaeus* that crossed over the gap at safe height increased after installation of the barrier screens at all sites. No increase was recorded for *Barbastella barbastellus*, 87% of which crossed above 4 m before screens were installed. No change in flight heights were observed for any of the three species at the control site. The percentage of *Myotis daubentonii* that crossed the gap at safe height above the screens varied between sites from 46% to 85%. Between 7% and 33% by-passed the screens and crossed the gap at low height at the end of the screens, up to 7% flew below 4 m height between the screens and up to 8 % of the bats abandoned their attempt to cross the gap. 61% of *Pipistrellus pygmaeus* and 89% of *Barbastella barbastellus* flew above both screens at safe height.

In a replicated, site comparative study, Naturalia Environnement & FRAPNA (2015, 2016) monitored bat activity near two gantries, a ramp which could function as a hop-over, two large underpasses constructed for large mammals and two large river culverts at the A89 motorway in France. The structures were monitored to assess their use and effectiveness of the mitigation measures for bats. The motorway traverses a forested mosaic landscape of national interest for bats. Bat activity was recorded acoustically for seven nights in each month from May to October in 2014 and 2015. Flight patterns were also monitored at the bat gantries with a thermographic camera for three nights at the gantries and the ramp in May, July/August and September in 2014 and 2015.
Bat activity at the ramp was relatively low compared to the activity at the other bat mitigation measures. The species composition at the ramp site was dominated by *Pipistrellus* bats (2014: 79%, 2015: 89%), *Myotis* bats (2014: 11%, 2015: 1%) and *Barbastella barbastellus* (2014: 8 %, 2015: 9%). No bats were observed crossing the motorway using the ramp in 2014. In 2015, 5 bats were observed to cross the motorway at the ramp, while 11 bats turned back and did not cross the road. 25 bats crossed the road but did not use the ramp.

In a controlled, site comparative study, Lüttmann (2012, 2013) compared road stretches with and without screens as bat mitigation. Five sites where roads intersected bat commuting routes were selected in a woodland and open field landscape. The sites consisted of two road stretches (a two-lane road and a four-lane motorway) with screens, a four-lane road with screens including a screen in the central reservation, a four-lane motorway without screens or other mitigation, and a 2-lane road with trees forming a natural hop-over. Each site was examined for at least 15 nights using bat detectors combined with infrared spotlights and cameras. Flight altitude of *Myotis* and *Pipistrellus* bats crossing the road was significantly higher in road sections with fences than in sections without screens. The result is based on the sum of a number of observations of bat crossings on road stretches without (*Myotis*: n=151, *Pipistrellus*: n=419) and with screens (*Myotis*: n=83, *Pipistrellus*: n=293). A similar picture was found at the road stretch with natural hop-overs. The screens also caused an increased movement of bats along the fenced road stretches. Many bats road flew along the screens, including the screen at the central reservation.

Rhinolophus ferrumequinum and other bat species have been observed crossing over a motorway at safe height at a site with trees on the central reservation in southern France (ChiroMed 2014). The road verges were elevated at the site. Bat carcass searches showed no mortality at this site, and the author relates this to the presence of this natural hop-over. Observations from other locations along the carriageway showed that sectors with longitudinal hedges were widely used as crossing areas and that the species preferred to cross the motorway where there were gaps in hedges, thus avoiding flying above the tree tops.

Prescher (2014) observed bat activity at four sites with road-severed treelines at a single carriageway in the Netherlands. *Nyctalus noctula, Eptesicus serotinus, Pipistrellus nathusii, Pipistrellus pipistrellus, Plecotus auritus, Myotis daubentonii,* and *Myotis dasycneme* were observed crossing the carriageway at the severed treelines. The flight heights of the bats when crossing the road were not recorded.

Various mitigation measures (culverts, fencing, planting and regular trimming of vegetation, panels on footbridge, light deterrence and enhancements of roosting sites) were installed to help *Rhinolophus hipposideros* in particular, to safely cross an upgraded main road and maintain the population in Wales, United Kingdom (Billington 2013, Picard 2014). The effects were assessed in a before-and-after study and counts of nursery roost size. One of the mitigation measures consisted of gently-sloping earth banks along each side of the road with planted trees on them. The earth banks were lowest furthest away from the road and sloped gently upwards towards the road where they ended steeply (false cuttings). Their purpose was to extend the canopy level towards the road in an attempt to raise the flight height of bats crossing the road. Billington (2013) reported that these earth banks with planted trees had a dramatic effect of 'pulling' the majority of the horseshoe bats to cross in this area. Crossing height was strongly correlated to embankment height, suggesting that elevated slopes may have some value in mitigation.

Flight paths of *Plecotus auritus* were mapped in the vicinity of natural hop-overs at a road which was to be expanded (Schut et al. 2013). By radio tracking 16 individuals, the authors found that the animals flew almost exclusively along hedgerows and treelines in the open landscapes in the study area. Width and species composition of the hedgerows or treelines did not affect their use as commuting routes by the bats. Six bats were tracked while crossing the road at ten different locations. Crowns of trees spanning the road leaving gaps above the road no larger than 6.5 m characterized nine of these locations. In some instances, bats made detours to cross the road at these locations.

Abbott et al. (2012a) made a replicated, site comparison and controlled study in 2008 at 25 under- and overcrossing routes on a motorway in agricultural and woodland habitat in Ireland. Bat activity was recorded acoustically on two nights at five river bridges, a culvert, seven road underpasses, six road overbridges and six severed hedgerows with mature trees. The gap sizes in the road-severed treelines were 49-72 m. The treelines ended abruptly at the motorway verges and the vegetation was not managed as a hop-over site. All bat species found in the adjacent habitat (*Pipistrellus pygmaeus, Pipistrellus pipistrellus, Myotis* spp. (potentially *Myotis daubentonii, Myotis nattereri*, or *Myotis mystacinus*) and *Plecotus auritus*), excluding the range-restricted *R. hipposideros*, were detected flying across the motorway between severed treelines. *Myotis* spp. and *Plecotus auritus*, comprised an unexpectedly high proportion (19.6%) of the total bat passes recorded over motorway traffic lanes at severed treelines.

A North-american study (Russell et al. 2009) assessed the level of mortality from road kills on a colony of *Myotis lucifugus* and *Myotis sodalis*. The study verified which species were being killed in traffic and examined the influence of canopy height and structure on flight behaviour. On 10 evenings between 15 May and 26 July 2001, bats were counted as they emerged from day roosts and crossed a heavily trafficked motorway en route to foraging areas. 26,442 bats were observed crossing this motorway over 9.29 h of observation.
Bats consistently used canopy cover when approaching the motorway from roosts. Most bats (58%) crossed the road at two sites where adjacent canopy cover was >20m. At a site where

canopy cover was lacking adjacent to the motorway, fewer bats were counted crossing (8%), and at a site where adjacent canopy was low (<6 m), 34% of bats crossed; generally flying lower and closer to traffic. There were no details on the proportion of bats crossing at traffic height vs safe height at each site. The authors conclude from their results that the best landscape feature for bats commuting across a motorway would be >20 m high trees immediately adjacent to the road.

An experimental and replicated study was designed to clarify whether hop-overs made from screens comprise an effective mitigation measure for *Rhinolophus hipposideros* by preventing bats from crossing roads at low altitudes with high risk of collision (SWILD & NACHTaktiv 2007). On three locations close to *Rhinolophus hipposideros* maternity roosts, two parallel 20 m long and 4 m high screens were placed across the preferred flight path. The screens were placed 5 m, 8 m, and 12 m apart, corresponding to standard road widths. Bat activity at the screens was monitored acoustically and with IR-cameras. The results at each site were compared to control setups without screens. 1561 bat passages were registered. The results clearly show that *Rhinolophus hipposideros* were deflected by the screens. Of the 1126 bat passages registered during the three experiments, only 45 were passages over both screens; the number of passages over the screens decreased with increasing gap distance. The remaining passages registered were all detours made by the bats to avoid flying over the screens. The bats often flew along the screens and crossed the gap at the ends of the screens at low height with collision risk. In 98% of 965 bat passes at set-ups with or without screens, bats flew <3 m above the road; the average flight height was 1.30 m. Screens only increased flight height by 50 cm; most often bats decreased their flight height after passing the first screen. However, the study shows that 4 m high screens can effectively deflect *Rhinolophus hipposideros*, and could help direct bats to safe crossing points.

Assessment and recommendations

We found ten studies aiming to evaluate the use or effectiveness of hop-overs. Three of those studies were controlled. Three studies investigated screens, two investigated earth banks or ramps, and five studies examined severed treelines as natural hop-over structures, where no focused management of the vegetation had been applied. Although the hop-overs showed some potential for reducing bat-vehicle collision risk for some species at some sites, none of the hop-over structures in the ten studies accomplished to increase the bats' flight height so that 90% of the bats would cross the roads at safe height above the road traffic.

Based on a comprehensive experiment showing that *Rhinolophus hipposideros* largely avoid flying over fences (SWILD & NACHT*aktiv* 2007) and that when they do, they quickly descent to their previous, low flight height (Billington 2001, 2002, 2003 *in* Wray 2006 and SWILD & NACHTaktiv 2007) we find there is considerable evidence that fence/screen hop-overs do not work for this species. We do not expect that such hop-overs will be effective for other low-flying and extremely manoeuvrable species (Group A: *Myotis bechsteinii, Myotis emarginatus, Myotis nattereri, Plecotus auritus, Plecotus austriacus,* and *Plecotus macrobullaris*) either. However, studies indicate that screen hop-overs could be more effective for less manoeuvrable species such as *Myotis daubentonii, Myotis brandtii/mystacinus, Myotis myotis* and *Pipistrellus pygmaeus and Pipistrellus pipistrellus* (Lüttmann 2012, 2013, Christensen et al. 2016). More research is needed to show if hop-overs can be designed as effective mitigation measure for such species, guiding 90% of the bats safely across roads.

Earth banks as hop-overs were only examined in two studies; in one study *Rhinolophus hipposideros* crossing height was strongly correlated with embankment height (Picard 2014), but the proportion of bats crossing at safe height was not recorded. In the other study an earth bank on one side of the road was only used by a very low number of bats (Naturalia Environnement & FRAPNA 2015, 2016). However, the strong correlation between the height of the road verges and flight height of bats when crossing the road, which was also observed for more common bat species by Berthinussen & Altringham (2012), suggests that ramps or embankments along roads could reduce collision risk by increasing the bats' flight height above traffic.

We found no studies of the effectiveness of tree and shrub hop-overs planted and maintained particularly to facilitate bats to cross at safe heights. Several studies described observations of bats that used severed treelines as hop-overs, but the flight height of the bats or the proportion of bats crossing the road at safe and unsafe heights was not reported in these descriptive studies. However, the studies indicated that the height of the trees near the road and the flight height for North American bat species were correlated (Russel et al. 2009), and that hop-overs with a relatively short distance between tree crowns are preferred to hop-overs with longer distances by *Plecotus auritus* (Schut et al. 2013). *Myotis bechsteinii* and *Rhinolophus ferrumequinum* have been observed to cross over two-lane roads at safe heights at road sections with a connecting tree canopy above the road (Kerth & Melber 2009, Nowicki et al. 2016).

The use and effectiveness of the examined hop-overs was species dependent. It likely also varies with hop-over design and factors such as topography and adjacent landscape elements, which were not well described in most of the papers. We note a lack of well-designed investigations of the effectiveness of different hop-over designs and analysis of the potential landscape factors which may explain some of the variation in effectiveness of hop-overs between sites and species. With the present level of evidence of effectiveness of hop-overs, we cannot generally recommend this mitigation measure. However, as some of the investigations showed that some bat species may raise their flight height above the traffic, the measure may have potential if properly designed and used only as mitigation measure for species with less to medium manoeuvrability (Groups C, D, and E). The measure could also be tested further for more manoeuvrable bats (Group B), but with extreme caution, as these species have a tendency to low flight and could fly low between the two hop-over structures.

However, we are sceptical towards hop-overs exclusively made from trees or shrubs because the vegetation require regular maintenance to obtain and maintain a dense structure with no gaps which bats may fly through. For many road-agencies, such ongoing maintenance seems not to be prioritised. If the vegetation is not maintained optimally, the hop-over could eventually result in increased mortality rates. Furthermore, a hop-over may function as an ecological trap, if the bats forage over a road section sheltered by shrubs and trees on the road verges.

To elucidate the potentials of hop-overs as a mitigation measure for bats we strongly recommend more research on hop-over designs that include screens and earth-banks, particularly as a mitigation measure for less manoeuvrable bat species flying at low or medium heights when crossing open gaps in a flight path. Such hop-overs could be combined with tree or shrub vegetation.

We also encourage the testing of screen hop-overs on elevated road stretches (e.g. viaduct bridges) where they might prevent less manoeuvrable, medium or high flying species from the genuera *Pipistrellus, Eptesicus* and *Nyctalus* from accessing the road and may guide the bats across the road at safe heights (Bach 2008, Bach & Bach 2008).

3.1.3 Wildlife overpasses

A wildlife overpass is a vegetated overbridge constructed across large transport infrastructures to maintain landscape connectivity for the fauna (Iuell et al. 2003, Brinkmann et al. 2012). Sometimes wildlife overpasses are combined with minor roads, forest tracks and recreational paths. In this category we included the results of a survey of a bridge with shrubs or small trees contained in planters but specifically constructed to maintain existing bat commuting routes.

Summaries

Two wildlife overpasses were examined in a controlled study to determine their effectiveness in guiding bats over the road safely in the United Kingdom (Berthinussen & Altringham 2015). Scotney Castle wildlife overpass is 30 m wide, well planted with shrubs and trees (2-3 m in height in 2015), woven wooden fencing and carries a minor road. It is well connected on both sides to mature trees and woodland. The Gwynedd (Porthmadog Bypass) overpass is not a typical wildlife overpass; it was constructed to maintain an existing bat commuting route. Woven wooden fencing has been installed to guide commuting bats to the overpass. The construction itself has vertical sides (approximately 2 m high) and a line of deadwood and planters containing hawthorn (*Crataegus monogyna)*.
Six and ten acoustic and visual surveys were conducted at each wildlife overpass by two observers standing on each side of the road. Flight height, direction, distance from the crossing structure and time of crossing were recorded for each passing bat. Significantly more bats used the Scotney Castle wildlife overpass to cross the road (97%, all flying over the bridge) than crossed the road near the bridge at unsafe heights (2%). At least five species were recorded using the bridge to cross the road and forage. *Pipistrellus pipistrellus*, the most abundant species, used the bridge more often (98%) than crossed the road below at unsafe heights (1%). *Pipistrellus pygmaeus*, the second most abundant species, was only recorded crossing over the bridge, as was *Myotis nattereri* and *Myotis brandtii/mystacinus.* Significantly more bats crossed the road using the Gwynedd wildlife overpass (62% within 2 m and 65% within 5 m) than crossed the road below at unsafe heights next to the structure (19%). Six species (*Pipistrellus pygmaeus, Pipistrellus pipistrellus, Plecotus auritus, Rhinolophus hipposideros, Myotis nattereri, Myotis brandtii/mystacinus*) were recorded using the bridge to cross the road. *Pipistrellus pygmaeus*, the most abundant species, 'used' the bridge significantly more often (71% within 2 m and 75% within 5 m) than crossed the road below at unsafe heights (17%). *Pipistrellus pipistrellus*, the second most abundant species, used the bridge less frequently, and no significant difference was found between the number of bats crossing unsafely (27%) and using the bridge within 2 or 5 m. The remaining species all crossed the road more often using the bridge than crossing unsafely below, but numbers were too low for statistical analysis.

In a replicated, controlled and site comparative study bat activity was monitored at four wildlife overpasses constructed for large mammals at a motorway in Poland (Cichocki 2015). The purpose of the monitoring was to assess bats' use of wildlife overpasses to cross the motorway barrier in a mixed agricultural and forested landscape. Bats were also monitored along road sections next to the wildlife overpasses as controls and at three bat gantries, road overbridges and underpasses for large mammals and watercourses for comparison. Bat activity was recorded once a week in March-November from 2012 to 2014.
The preliminary results suggest that bats only used the wildlife overpasses occasionally. Bats commuted and foraged intensively along the forest edges next to the highway. At the time of the study, the wildlife overpasses were only a few years old and the planted vegetation had not developed a dense structure. The authors suggest that the lack of vegetation at the approach ramps and on the wildlife overpasses is a contributing factor to the low usage by bats.

A descriptive study monitored bats on two wildlife overpasses linking extensive forest habitats on both sides of a main carriageway in Catalonia (Rosell et al. 2015, 2016). The wildlife overpasses were well connected to the forest on each side of the road, but the vegetation on the overpasses only consisted of herbs and a little shrub. Sampling was performed during three hours on 22 consecutive nights in spring 2015 using an automatic ultrasound recorder placed on the wildlife overpasses and in the woodland 150 m from the overpasses. Eleven species or species-groups were detected on the wildlife overpasses (2609 bat calls, mostly from commuting bats: *Rhinolophus ferrumequinum, Rhinolophus hipposideros, Myotis myotis/blythii, Myotis emarginatus, Myotis daubentonii/capaccinii, Pipistrellus pipistrellus, Pipistrellus kuhlii/nathusii, Pipistrellus pygmaeus/Miniopterus schreibersii, Hypsugo savii, Nyctalus leisleri/Eptesicus serotinus, Barbastella barbastellus*) and only five in the woodland (167 bat calls). Species-groups detected on the wildlife overpass but not in the woodland were both from low- and high-flying species-groups. 90% of the recorded calls were from common species-groups: *Pipistrellus* or *Nyctalus leisleri/Eptesicus serotinus*. 95% of the recorded bats were commuting. The result indicates that wildlife overpasses were used intensively by bats when comparing to bat activity in the forest, but there is no evidence for its effectiveness.

In a small descriptive, non-controlled study, the bat activity on a wildlife overpass (“De Munt”) across a motorway and a high-speed rail in Belgium was monitored (Emond et al. 2015). The development of vegetation and usage by animals including bats was registered. Bats were monitored acoustically. The bridge was used by *Pipistrellus pipistrellus*, *Pipistrellus nathusii* and *Eptesicus serotinus*, but for incidental foraging, not as a standard flying route. The wildlife overpass contained a few small pools that were used by *Myotis daubentonii* for foraging on a few occasions.

In a series of descriptive, non-controlled studies, Emond & Brandjes (2014a, 2014b, 2014c, 2015) registered bat activity on four wildlife overpasses over motorways in the Netherlands using automatic ultrasound detectors placed on the bridges. Monitoring was carried out for two to three nights during each of the months July, August, and occasionally in September.
On the wildlife overpass “Hoog Buurlo”, hunting activity by *Pipistrellus pipistrellus*, *Eptesicus serotinus*, and *Nyctalus noctula* was recorded in July and August (Emond & Brandjes 2014a). A *Myotis* bat was also registered on one night. However, most recordings indicated that bats used of the wildlife overpass as a flying route to cross the motorway.
The wildlife overpass "Hulshorst" was primarily used as a flying route to cross the motorway by *Pipistrellus pipistrellus*, *Pipistrellus nathusii, Eptesicus serotinus*, and *Nyctalus noctula*, as well as *Myotis* spp. (Emond & Brandjes 2014b). Some foraging behaviour was also recorded on the wildlife overpass.
On the wildlife overpass "Petrae” (Emond & Brandjes 2014c), only few bats were detected; two recordings of a passing *Pipistrellus pipistrellus*, one hunting *Eptesicus serotinus,* and two passing *Nyctalus noctula*.
On the wildlife overpass "J. P. Thijsse” (Emond & Brandjes 2015), *Pipistrellus pipistrellus* was recorded quite numerously, and *Eptesicus serotinus*, *Nyctalus noctula*, and *Pipistrellus nathusii* were also registered. A few *Myotis* recordings were made. Most of the recorded bats were commuting across the motorway over the wildlife overpass, but some hunting activity was also recorded.

A replicated, partially controlled study (Ransmayr et al. 2014b) aimed to determine whether road overbridges over larger roads were used as crossing structures by bats in the same way as wildlife overpasses, and if so, whether they were used to the same extent as wildlife overpasses.

Bat crossings at four road overbridges and one wildlife overpass were observed three nights during May, June/July, and August, respectively. Observations were carried out using a thermographic camera synchronized with at least three automatic ultrasound recorders (one on each end of the bridges and one in the middle). In addition, visual observation was performed at dusk by two persons. All bridges were well connected with the surrounding landscape by forests, hedgerows or treelines. Bat activity was also monitored at three potential bat crossing sites; one near the wildlife overpass (at a severed hedgerow) and two near two of the road overbridges (a wide, severed hedgerow and a steel road sign structure that resembled a bat gantry).
Many bats used the wildlife overpass to cross the road, even though it only had sparse, young tree vegetation. The three potential bat crossing sites without mitigation structures were not or very rarely used by bats.

Lambrechts et al. (2008, 2011, 2014) monitored the Kikbeek wildlife overpass in Belgium on two nights during summer in the first, fourth and seventh year after construction. The wildlife overpass is located in a large forest transected by a motorway. Bat activity was recorded with ultrasound detectors at the entrance of the wildlife overpass and at the middle of the bridge. Initially, *Pipistrellus pipistrellus* was observed most frequently and foraged above and around the bridge. *Pipistrellus nathusii* was heard passing above the wildlife overpass on a few occasions and was also observed foraging. Distant *Nyctalus noctula* were registered a few times, but the species did not seem to use the wildlife overpass. Individuals of the genus *Myotis* were frequently registered using the wildlife overpass. *Myotis daubentonii* was hunting above a small wetland constructed on the bridge. A few passes of *Myotis nattereri* and *Plecotus sp.* were registered on the bridge. In the fourth year also *Eptesicus serotinus* was detected, and in the seventh year *Nyctalus leisleri* was heard. Comparing bat activity between years indicates an increase in use of the wildlife overpass by *Eptesicus serotinus, Myotis sp.* and *Pipistrellus nathusii*, while *Pipistrellus pipistrellus* activity appeared to decline for unknown reasons.

In a non-controlled, descriptive study, Lambrechts et al. (2007, 2010, 2013) monitored the use of a Belgian wildlife overpass (De Warande) by bats (and other wildlife species) in the first, fourth and seventh year after construction. The wildlife overpass is located in a large forest area transected by a major carriageway. Bat activity was recorded with ultrasound detectors at the entrance of the wildlife overpass and in the middle of the bridge. Bats were monitored for two nights in June and in August in each survey year.
The wildlife overpass was used by *Nyctalus noctula*, Nyctalus leisleri, *Pipistrellus pipistrellus, Pipistrellus nathusii, Myotis daubentoni,* and *Plecotus* sp. All species were hunting at the wildlife overpass; both *Nyctalus* species were probably attracted by insects flying above the heated concrete structures. Twice a *Myotis nattereri* was observed crossing the wildlife overpass.

A before-and-after study at a German motorway investigated the habitat use of *Myotis bechsteinii* before and after the construction of a wildlife overpass over an existing motorway in Germany (Stephan et al. 2012). The study focused on a maternity colony of approximately 100 adult females in a forest intersected by the motorway. The spatial behaviour of the colony was monitored via radiotracking of 19 females in 2006, 2008 and 2009. In 2006, before the wildlife overpass was built, half of the radio-tracked females crossed the motorway each night, foraging on both sides, in spite of the complete absence of connecting elements bridging the motorway. Already one month after opening the wildlife overpass in 2008 it was used by bats - the majority being *M. bechsteinii*. In 2008 and 2009, the colony foraged and roosted on both sides of the motorway. This was the authors' first experience of roost switching over the heavily used motorway. After the wildlife overpass was built,, significantly more radiotracked individuals had home ranges that included areas on both sides of the motorway. No information on roadkills was stated.

A replicated, site comparison study of bat occurrence at two narrow wildlife overpasses over a carriageway was carried out in August in Denmark (Elmeros et al. 2011). The wildlife overpasses were constructed for medium and large sized mammals in an area with agricultural land, woods and wetland habitats. The structures were 14 m and 15 m wide and elevated compared to the surrounding terrain, planted with shrubby vegetation and fences on the sides to shield off light and noise from the traffic below. Bat activity was recorded simultaneously with automatic ultrasound detectors on the wildlife overpass and ca. 100 m from the bridges at an adjacent linear habitat. Bats were also recorded with hand-held ultrasound detectors in combination with visual observation.
All bat species that were recorded in the adjacent habitats were also recorded on the wildlife overpasses (*Myotis daubentonii, Pipistrellus nathusii, Nyctalus noctula, Eptesicus serotinus, Vespertilio murinus*). No bats were observed visually crossing the road at the wildlife overpasses or near the adjacent linear habitats. The monitoring intensity and total bat activity was low (3 nights). The structures were four years old and the vegetation on the wildlife overpasses was low and open.

In a descriptive site comparison study, Bach & Müller-Stieß (2005) examined eight wildlife overpasses, three road overbridges, and four technical road underpasses. None of the structures were made specifically as fauna passages for bats. The wildlife overpasses were examined by means of acoustic and visual observation, and in some cases by means of mist netting. Each structure was monitored for two to four nights. Bat activity was defined as number of bat calls (recordings) per hour. The wildlife overpasses were used by ten bat species (*Nyctalus noctula, Eptesicus serotinus, Myotis brandtii/mystacinus, Myotis bechsteinii, Myotis nattereri, Myotis myotis, Myotis daubentonii, Plecotus auritus/austriacus, Pipistrellus nathusii, Pipistrellus pipistrellus*), representing a minimum of 60-80% of the species present in the area. The species not registered on the wildlife overpasses were either rare, difficult to detect, or not relying on guiding structures. Wildlife overpasses with high activity levels were, as a rule, characterized by connecting vegetation structures such as tree lines and forests. The authors found that there was a small, positive correlation between bats' use of wildlife overpasses and the width of the bridge. Wildlife overpasses were used more intensely than road bridges but a little less than road underpasses.

Fuhrmann & Kiefer (1996) conducted a 2-year experimental study in order to find methods to prevent road mortality of *Myotis myotis* as a new road was planned on a former railway embankment directly in front of the old station building containing around 220 roosting females. Flight paths of "undisturbed bats" were registered during the first year (1991) using bat detectors and a night vision scope. During the winter 1991/1992, an 80m long and 4-5m high construction was erected in front of the station building in the main flight path of the bats. During 1992, it was modified to simulate an underpass and a bridge, and the resulting flight paths of the colony were registered during three experimental setups: 1) an 8 m wide gap was formed in the construction for the bats to fly through. No guiding walls were leading to the gap; 2) underpass simulation: an 8 m wide gap in the lower part of the construction (0 - 2.3 m above the ground), guiding walls leading from the roost building to the gap; 3) bridge simulation: an 8-16 m wide gap in the upper part of the construction (2.3 – 4-5 m above the ground), guiding walls leading from the roost building to the gap. The results were not analysed statistically.
Without modifications (baseline, 1991): more than 80% of the registered bats flew low over the railway embankment as they emerged in the evening. The experimental construction was used by the bats in the following ways: 1) in April, 3% of the registered bats passed through the gap. In July, the amount had risen to 48%, 2) the simulated underpass was used by up to

65% of the registered bats, 3) the simulated bridge was used by up to 87% of the registered bats; the best results were obtained with a 16m wide gap (as opposed to 8 m). The guiding walls seemed to be crucial to make the bats use the experimental construction.

Assessment and recommendations

We found 15 studies, which examined bats' use of wildlife overpasses. Only one of the overpasses in the reviewed studies was designed particularly for bats. Most studies only focused on bat activity on the wildlife overpasses, and did not determine how effective the overpasses were. In many cases, there was no visual observation, resulting in uncertainty about bat flight patterns over the wildlife overpasses.

Two studies were controlled and recorded bats both on the bridge and on the road below. One of these studies determined that more than 90% (97%) of the bats were guided safely over the road by the bridge (Berthinussen & Altringham 2015). A before-and-after study did not measure effectiveness but provided evidence that a wildlife overpass enabled *Myotis bechsteinii* to expand their territory and overcome the barrier effect of a motorway (Stephan et al. 2012).

Results indicated that vegetation on the wildlife overpass and connecting elements such as hedges, treelines or forests were very important factors in determining the use of the wildlife overpasses (Berthinussen & Altringham 2015, Bach & Müller-Stieß 2005, Cichocki 2015). Two studies also suggested that wider bridges might be more effective than narrower bridges (Berthinussen & Altringham 2015, Bach & Müller-Stieß 2005).

Bats of all species groups ranging from low flying, extremely manoeuvrable species to high flying, less manoeuvrable bats were recorded on the wildlife overpasses e.g. *Rhinolophus ferrumequinum, Rhinolophus hipposideros, Plecotus auritus, Plecotus auritus/austriacus, Myotis bechsteinii, Myotis nattereri, Myotis myotis, Myotis myotis/Myotis blythii, Myotis emarginatus, Myotis daubentonii, Myotis daubentonii/Myotis capaccinii, Myotis brandtii/Myotis mystacinus, Pipistrellus pipistrellus, Pipistrellus pygmaeus, Pipistrellus pygmaeus, Miniopterus schreibersii, Pipistrellus nathusii, Pipistrellus kuhlii, Hypsugo savii, Nyctalus noctula, Nyctalus leisleri, Eptesicus serotinus, Vespertilio murinus, Barbastella barbastellus*.

However, it should be noted that many of the studies contributing to this species list did not use visual observation, and therefore it remains uncertain which proportions of the recorded bat passes actually used wildlife overpasses to cross the road. That uncertainty is related primarily to high flying species using long range echolocation calls (mostly bats from categories E and D).

The effectiveness of wildlife overpasses as migitation measures for bats is not well documented. Only two of the studies (examining six bridges between them) were designed to test the effectiveness of wildlife overpasses for bats; the remaining studies only examined bats' use of the bridges. The fact that only one of the 27 examined bridges was constructed particularly for bats may also affect how much bats used them. Furthermore, most studies were performed before dense, mature vegetation had developed across the wildlife overpasses and the approaches to the structures. The composition of the vegetation on the wildlife overpass and connectivity to the surrounding landscape is significant for bat activity on the wildlife overpasses and most likely key to the effectiveness of overpasses (Bach & Müller-Stieß 2005). The lack of mature vegetation probably constitutes an essential limitation in the studies to provide evidence for the potential of wildlife overpasses as effective passages for bats.

However, bats use of wildlife overpasses was generally high, and we consider wildlife overpasses to have a high potential as effective bat mitigation structures. In contrast to most other mitigation measures, well designed green bridges are probably effective for the majority of European bat species regardless of their flight patterns and manoeuvrability. Wildlife overpasses designed and placed particularly to guide bats safely across roads may prove more effective than most present wildlife overpasses, which have been installed primarily to guide larger mammal species safely across the roads.

Further studies to confirm the potential effectiveness of wildlife overpasses are needed. We encourage more site comparison studies of wildlife overpasses of different age classes and with different vegetation structure and connectivity to surrounding bat habitats. Long-term studies of some wildlife overpasses should be performed as well. To evaluate effectiveness rather than use, it is essential to record bat activity and flight behaviour on the wildlife overpasses, as well as the number of bats crossing directly over the road near the wildlife overpass and at road stretches with similar neighbouring landscape.

3.1.4 Modified bridges, road bridges and other technical structures

When commuting across roads, echolocating bats may use road, bicycle and pedestrian bridges as well as other technical structures such as road information signs forming gantries across roads, as guiding structures (e.g. Bach et al. 2004, Abbott et al. 2012a, Ransmyr et al. 2014b, Cichocki 2015, V.Loehr, pers. comm.).
Overbridges can be modified in a number of ways to enhance their suitability as bat crossing structures. Panels can be installed on the side(s) of existing bridges to guide commuting bats and shelter them from streetlights and light and noise from vehicles on the road below. Alternatively, narrow green verges can be provided on one or either side of the bridge (e.g. NACHTaktiv & SWILD 2014).

Summaries

Berthinussen & Altringham (2015) recorded bat activity at a road overbridge, which had been constructed near a bat commuting route transected by a new dual carriageway bypass. The bridge was not connected to the surrounding habitats by hedges or similar structures. Six surveys were completed. Three bats were observed to cross the road; one *Pipistrellus pipistrellus* at 2 m height and 12 m away from the overbridge, a *Nyctalus/Eptesicus* at 12 m height and 20 m from the overbridge, and an unidentified bat at 6 m height and 14 m from the overbridge. No bats were recorded using the overbridge as a guiding structure.

In a replicated, controlled, site comparison study Cichocki (2015) monitored bats' use of a road and a railway overbridge as potential passages for bats across a motorway in Poland. Bat activity was also recorded at bat gantries, underpasses for large mammals and watercourses, at wildlife overpasses constructed for large mammals and at road underpasses. Bat activity was recorded once a week in March-November from 2012 to 2014. The activity was recorded at the overbridges and along two 250 m transects on each side of the overbridges with ultrasound detectors, infrared cameras and visual observation.
The highest number of bats crossing the highway via any overpasses (gantries, wildlife overpasses and road and railway overbridges) was recorded at the railway overbridge (numbers and species not stated). The clearance for the railway through the adjacent forest habitats functioned as a flight corridor for bats. A dense woodland cover close to the highway around the railway overbridge may govern the high use of this overbridge compared to the road overbridge and wildlife overpasses which are not well connected by tall vegetation to the adjacent woodland edges. Furthermore, the author's highlight that bats did not have to change flight altitude to cross the motorway via the railway overbridge as it is level with the

adjacent terrain, while the wildlife overpasses and the road overbridge were elevated compared to the surrounding terrain.

A replicated, partially controlled study (Ransmayr et al. 2014b) aimed to determine whether road overbridges over larger roads were used as crossing structures by bats in the same way as wildlife overpasses are used, and if so, whether they were used to the same extent as wildlife overpasses.
Bat crossings at four road overbridges and one wildlife overpass were observed for three nights during May, June/July, and August, respectively. Observations were carried out using a thermographic camera synchronized with at least three automatic ultrasound recorders (one on each end of the bridge and one in the middle). In addition, two persons performed visual observation at dusk. All bridges were well connected with the surrounding landscape by forests or hedgerows/treelines. Bat activity was also monitored at three potential bat crossing sites; one near the wildlife overpass (at a severed hedgerow) and two near two of the road overbridges (a wide, severed hedgerow and a steel road sign structure that resemble a bat gantry).
The authors conclude that road overbridges can in some cases help bats cross roads safely, but the results were very heterogenous. Many bats used the wildlife overpass and one of the road overbridges to cross the road. A second bridge was less used, and the two remaining bridges were only used sporadically. The three potential bat crossing sites without mitigation structures were not or very rarely used by bats.

NACHTaktiv & SWILD (2014) monitored the *Rhinolophus hipposideros* population development and the development of use and effectiveness of a mitigation scheme on a motorway (since 2006) and a major carriageway (since 2009) in Saxony, Germany (NACHTaktiv & SWILD 2014, F. Bontadina, pers. comm.). The mitigation included modified road overbridges with green verges consisting of shrubs as guiding structures and fences to shield off light and noise from the road below, a wildlife overpass, underpasses, hedgerows to guide bats to the mitigation structures and barrier fences. Replicated recording of bats' use of mitigating structures was performed in the first years. The annual automatic acoustic monitoring is designed as a site comparative, controlled study using permanent acoustical recording between April and October in a culvert, on an adapted overbridge and at a control site at a commuting routes in the vicinity to the road. Bat activity on the modified bridge has been increasing annually as the shrubs and trees on the green verges of the bridges and in the hedgerows guiding bats to the mitigation structure have developed.

A LIFE project carried out in Provence, France, aimed, among other things, to provide innovative and effective tools to reduce mortality risk at road crossing sites for *Rhinolophus ferrumequinum* and *Myotis emarginatus* (ChiroMed 2014). The project tested the installation of fences on an overbridge carrying a two-lane carriageway. The 58 m long corridor was created by installing two parallel screens about 2 m high made from artificial hedge fleece on the side of the bridge. The site was close to known hunting grounds of both bat species, and bats crossed the dual carriageway near the over-bridge. Bat activity at the bridge was monitored by means of automatic ultrasound recorders as well as visual and thermal camera observations. Carcass searches were made along the road for 100 m in each direction from the bridge. Before the experiment, bats predominantly crossed the carriageway parallel to the bridge where trees on the central reservation created a natural hop-over. When the corridor on the bridge was completed, a few bats crossed the carriageway in close proximity to the outer screen of the corridor. Five weeks later more individuals flew above the corridor and occasionally dived down between the screens to travel in the corridor for a few metres. No individual was observed using the corridor in its entire length. No bat carcasses were found at the bridge, which the authors relate to the presence of the natural tree hop-over.

Mitigation measures (culverts, fencing, planting and regular trimming of vegetation, earth ramps, light deterrence and enhancements of roosting sites) were installed to help particularly *Rhinolophus hipposideros* safely cross an upgraded main road and maintain the population in Wales, United Kingdom (Billington 2013, Picard 2014). The effects were assessed in a before-and-after study and nursery roost counts. One of the mitigation measures consisted of attaching metal panels to the side of a footbridge to shield it from vehicle lights, and additional planting on both sides of the road to connect hedgerows to the bridge and create a flight corridor over the road. The adjustments were reported to have had some effect in helping bats safely across the road, but bat casualties were still found in the area around the footbridge after the adaptation was installed.

In a descriptive study the use of a modified agricultural bridge by *Rhinolophus hipposideros* and *Rhinolophus ferrumequinum* when commuting across a motorway in France was investigated over a five year period (Arthur et al. 2010, Burette 2013, L. Arthur, pers. comm.). During the monitoring period in 2013, the bridge was modified with to enhance the use of the bridge as a safe crossing site for highly photophobic bats, such as *Rhinolophus* sp. The panels reduce the light pollution from the motorway and provide stronger echos for the bats. Different types and heights of panels were tested. Bat activity and passages were recorded with bat detectors to determine flight trajectories.
Bat passages were monitored for five nights in 2012 and 2013, respectively (Burette 2013). *Rhinolophus* bats used the bridge to cross the dual carriageway and flew low along side the panels away from light pollution of the road. The numbers of passages by *Rhinolophus hipposideros* and *Rhinolophus ferrumequinum* in 2013 were not statistically different from the number observed the year before the panels were installed. However, later studies have shown that the numbers of both *Rhinolophus* species increased in 2014 and 2015 (L. Arthur, pers. comm.). The researchers suggest that the adapted bridge may function as an essential nocturnal ecological corridor for light sensitive bat species.

Abbott et al. (2012a) made a replicated, site comparison and controlled study at 25 under- and overcrossing routes on a motorway in agricultural and woodland habitat in Ireland. Bat activity was recorded acoustically on two nights at five viaduct bridges across rivers, one boxed shaped culvert, seven road tunnel underpasses carrying minor roads, six road overbridges and six severed treelines. None of the structures were designed as wildlife crossings. Bat activity was recorded above and below the motorway structures and in the adjacent habitat simultaneously. Bats (*Pipistrellus pipistrellus, Pipistrellus pygmaeus* and *Myotis* spp.) used under-motorway routes, particularly river bridges, more than over-motorway routes. *Rhinolophus hipposideros* was only recorded crossing the motorway under river bridges and underpasses. Activity was lower (by > 10%) at over-motorway crossing routes than in adjacent habitats. 50% of bat passes at overbridges were recorded below the structure, potentially exposing bats to motorway vehicle collision. *Nyctalys leisleri* comprised the largest percentage (41%) of the total bat passes at overbridges.

In the Netherlands, 14 locations with road overbridges, one location with a wildlife overpass and 15 control locations without over-structures were surveyed acoustically during 1-2 nights (Schut et al. 2011). The replicated, controlled study showed that at 90% of all 30 locations, activity of bats crossing the roads was 2-5 times lower than the activity measured at the structures leading to the intersections, indicating a road barrier effect. Bats crossed the road at 14 out of 15 locations with overbridges and at 10 out of 15 locations without (not statistically significant). Three times as many bats crossed the road at locations with overbridges than at locations without (statistically significant difference).

Bach et al. (2004) extracted data from an investigation in Hessen, Germany, where five overbridges were investigated during 2001 and 2002. All bridges connected forests or hedgerows leading to a village or a forest. The bridges were only used by a small number of bats comprising four species: *Pipistrellus pipistrellus, Myotis myotis, Myotis nattereri* and *Myotis brandtii/mystacinus.* The number of individuals and species using the overbridges were lower when compared to the tunnels investigated in the same study.

Assessment and recommendations

We found ten studies investigating bats' use of conventional or adapted overbridges. Seven of those compared bat activity at the bridges with the activity registered at other types of mitigation measures or at control sites. The studies investigated 32 overbridges altogether.

Unadapted overbridges were used significantly more than control sites without any crossing structures in two studies (Ransmayr et al. 2014, Schut et al. 2011). Underpasses were found to be used more than unmodified road overbridges in comparative studies (Abbott et al. 2012, Bach et al. 2004).
Two of the overbridges which were very well connected to the surrounding habitat by trees, bushes or forest, and positioned at existing commuting routes were well used by bats (Cichocki 2015). The use of modified overbridges increased with the development of the planted trees and shrubs leading to the bridge and on the bridge (NACHTaktiv & SWILD 2014, F. Bontadina pers. comm.).

The remaining three studies evaluated the effectiveness of installing panels on the bridges to shield the passage on the overbridge from the headlights of passing vehicles (Burette 2013, ChiroMed 2014, Picard 2014). One bridge was examined in each study. All three studies found an increase in bats' use of the overbridge after the modification. Two of the studies reported indications that the overbridges are used more with time and suggest that the efficiency of the bridges might increase with some years of habituation.

Four studies described visual observations of bats at the overbridges. A non-modified overbridge was not used by the passing bats (Berthinussen & Altringham 2015). Abbott et al. (2012) reported that 50% of bat passes at non-modified overbridges were recorded below the structure, potentially exposing bats to motorway vehicle collision. Bat passes at an overbridge modified with screens first occurred along the outer edge of the bridge, but gradually bats were observed in the corridor on the bridge itself (ChiroMed 2014).

None of the ten studies of adapted bridges or technical structures provided evidence that conventional or modified overbridges can help 90% of the bats crossing the road do so at safe heights. There is not enough evidence to recommend these structures as mitigation measures for bats. The studies suggest that overbridges adapted with vegetation or with screens are used by bats, but long-time studies are needed to determine how effective such modified bridges can be. Some of the studies also indicate that connectivity to the surrounding landscape (hedgerows, forest edges, etc.) is important to enhance the bats' use of conventional or adapted road overbridges.

Road overbridges and other technical structures are designed and located for other purposes than facilitating bats safely across roads. Only a small fraction of these structures are coincidentally located near bat flight paths, where modifications are most likely to have an effect. Hence, adaptations of overbridges and other road technical structures to enhance their effectiveness as bat mitigation structures may only be relevant in few cases. However, although the road overbridges and technical structures are constructed for other purposes than bat mitigation, they could provide additional safe crossing points to the mitigation provided by purpose-build fauna passages.

If adaption is possible, overbridges located near existing bat commuting routes have the potential to reduce the barrier effect and mortality risk of a road scheme, particularly overbridges adapted with green verges and hedgerows. Long-term use and increased effectiveness of adapted overbridges and technical structures might be achieved by improving connectivity to bat habitats and commuting routes, e.g. with hedgerows (NACHTaktiv & SWILD 2014).

3.2 Underpasses

Underpasses allow bats to pass under the road away from the traffic. They can be constructed specifically to facilitate safe passage for wildlife across the road infrastructure, for carrying drains or streams under the road, or they can be designed for trains, vehicles or people (Iuell et al. 2003, Limpens et al. 2005, Brinkmann et al. 2012). Underpasses comprise culverts and tunnels as well as the usually more spaceous viaducts and river bridges. Bats may regularly use underpasses that are designed as wildlife passages as well as underpasses that are used by humans for other purposes during the day but have little use in the night time, e.g. tunnels for minor roads, agricultural access roads, forest tracks and pedestrian paths (Bach et al. 2004, Abbott et al. 2012a, Berthinussen & Altringham 2012).

3.2.1 Culverts and tunnels

Culverts and tunnels are underpasses usually constructed where the road is raised onto an embankment (Iuell et al. 2003, Brinkmann et al. 2012). The height of the underpasses is limited by the height of the road embankment. Culverts carry streams or open drains under the roads, whereas tunnels are dry underpasses. Tunnels and large culverts with dry banks on one or both sides of the waterbody are sometimes constructed specifically as wildlife passages, but most often they are constructed for purposes other than wildlife. Multi-usage culverts are partially intended for wildlife but alsocarry agricultural tracksor paths for cyclists and pedestrians.

Summaries

Three tunnels were examined in a controlled study to determine their effectiveness as safe crossing sites for bats at carriageways in the UK (Berthinussen & Altringham 2015). Six to ten dusk or dawn surveys were conducted at each tunnel, with one observer positioned at one end of the underpass and one standing on the road above, equipped with bat detectors and night scopes. Flight height, direction, and time of crossing were recorded for each bat. The majority of bats on all three sites flew through the tunnels rather than over the carriageways above. However, at two of the tunnels one third of the bats still crossed above the carraigeways at unsafe heights. At the first of these tunnels (H 2.5 m, W 2.5 m, L 25 m), constructed particularly for wildlife including bats, all or nearly all individuals of *Myotis brandtii/mystacinus, Myotis nattereri* and *Rhinolophus hipposideros* used the tunnel, whereas *Pipistrellus pygmaeus, Pipistrellus pipistrellus* and *Plecotus auritus* only or predominantly crossed above the road at unsafe heights (< 5 m). Bats crossing above the road at the second tunnel (H 2. 5m, W 2.5 m, L 70 m) were not identified to species, but high numbers of *Rhinolophus hipposideros* as well as *Pipistrellus pipistrellus, Pipistrellus pygmaeus* and *Myotis* spp. were registered in the tunnel. Bat activity was largest at the third underpass, where 95% of all bats used the tunnel instead of crossing the road above. This tunnel had a larger cross-sectional area than the other two (H 4.5 m, W 4.5 m, L 45), and connected a pre-existing flight route. Furthermore, this tunnel did not require bats to alter their flight height to fly through it, as the other two tunnels did. *Pipistrellus pygmaeus* was most abundant and 96% of them used the tunnel to cross the road. The less abundant *Pipistrellus pipistrellus* followed the same pattern; 93% of those used the tunnel instead of crossing the road above at unsafe heights. All the remaining species (*Myotis brandtii/mystacinus, Myotis daubentonii, Rhinolophus hipposideros, Plecotus auritus, and Myotis nattereri*) were recorded flying through the tunnel but not over the road above.

In a replicated, controlled and site comparative study, bat activity was monitored at four tunnels constructed as fauna passages for large mammals, six culverts for watercourses, a low viaduct bridge over a river and six road tunnels to assess bats' use of these structures to cross the barrier created by a motorway in agricultural and forested landscape in Poland (Cichocki 2015). Bats were also monitored at three bat gantries and three wildlife overpasses constructed for large mammals for comparison. Unmitigated road stretches near the fauna passages and technical road structures were monitored as controls. Bat activity and roadkills were recorded once a week in March-November from 2012 to 2014.
The preliminary results suggest that the culverts and the viaduct were used most intensively by bats, possibly because the bats use the watercourses as commuting routes. Only a few fatalities were recorded (n=25). Most of these were *Nyctalus* and *Pipistrellus* bats.

In a replicated, site comparative study at a motorway in France, bat activity was recorded to assess effectiveness of two large tunnels constructed for large mammals and two large culverts with streams, two gantries and a hop-over ramp (Naturalia Environnement & FRAPNA 2015). The culverts were sufficiently wide to function as fauna passages for large mammals. The motorway traverses a forested mosaic landscape of national interest for bats. Bat activity in the underpasses was recorded acoustically for seven nights in each month from May to October in 2014. Bat activity on the motorway above the underpasses was not recorded. Average bat activity per night was generally higher in the four underpasses (420-1382 records/night) than at the gantries (134-422 records/night). The bat activity was higher in the two culverts than in the dry tunnels (wet: 1130 records/night, dry: 482 records/ night). *Pipistrellus* bats (96.2%) dominated the activity in both tunnels and culverts.

Use of agricultural underpasses by bats was described in a study in Northern Portugal (Barros 2014). Five tunnels on a road located in a rural agricultural and grazing area were selected. The average dimensions of the tunnels were H 4.25 m, W 9 m, L 34 m. The data was obtained through acoustic detection and mist net capture. Field work took place in August comprising one night for each underpass and method. Acoustic and mist netting results confirmed the use of the tunnels by at least 12 species (*Pipistrellus pipistrellus, Pipistrellus kuhlii, Pipistrellus pygmaeus, Myotis daubentonii, Myotis escalerai, Myotis myotis, Nyctalus leisleri, Plecotus austriacus, Rhinolophus ferrumequinum, Rhinolophus hipposideros, Rhinolophus mehelyi/euryale and Eptesicus serotinus/isabellinus*). For tunnels with the same height (4.2 - 4.3 m) and width (9 m), the most frequently used were the longest, although the number of species did not follow that pattern. Surrounding habitat may be a confounding factor.

To examine the extent that underpasses less than 4.5 m high were used by bats, Ransmayr and co-workers (2014a) tested bat use of three culverts in a non-controlled site comparison study. All three culverts were made to facilitate a water course passing below a larger road (motorway or main road). None of the passages were made particularly for bats. The dimensions of the three culverts were: Underpass A5: H 3 m, W 12 m, L 40 m, Underpass B15: H 1.7 m, W 18 m, L 30 m and Underpass A3: H 2.3 m, W 9 m, L 28 m. At the first culvert, there were barrier screens on both road verges above the underpass. At the second, there was a barrier screen on one of the road verges, and at the last underpass there were no screens on the road verges above the underpass. All the culverts were well connected by hedges or treelines to the surrounding landscape. The field work took place during June-September 2013. On 3 x 4 nights (2 x 4 nights at underpass A3), bat activity was monitored

by an automatic ultrasound recorder placed in the centre of the culvert, and one at one of the entrances of the culvert. Furthermore, activity was monitored manually (detector and visual) and with additional automatic ultrasound recorders outside the culverts on 2 nights at each culvert.
Underpass A5: *Myotis daubentonii* was registered more frequently inside than outside the passage, indicating hunting behaviour that was confirmed by registered feeding buzzes inside the culvert. *Myotis myotis* was also registered most frequently inside the culvert, but with a small total number of registrations. *Pipistrellus pipistrellus* and *Nyctalus noctula* were registered significantly more often outside the culvert than inside. Underpass B15: Only *Myotis alcathoe* (and *Myotis* sp.) was registered significantly more inside than outside the passage and with a small total number of observations. *Plecotus* spp., *Hypsugo savii, Pipistrellus pipistrellus* and *Pipistrellus pygmaeus*, and *Nyctalus noctula* were registered significantly more often outside the culvert than inside. Underpass A3: At this passage, the number of (identified) bat calls was quite low, and only *Myotis daubentonii* was registered significantly more inside than outside the passage. *Nyctalus noctula* was registered significantly more often outside the culvert than inside.

Møller et al. (2014) conducted a controlled site-comparison study to examine bats use of two culverts leading watercourses under a motorway. The two culverts had almost the same tunnel indices but different cross sectional areas: Culvert A: H 1.4m, W 7.2m, L 24m, Culvert B: H 2.4m, W 5.6m, L 30m. Culvert A only had hedge/tree vegetation on the stream verges on one side of the motorway, while culvert B was well connected to the surrounding landscape by hedge/tree vegetation on both sides. The field work took place during June-September 2013. On 6 nights (4 nights at culvert B), bat activity was monitored by five synchronized automatic ultrasound recorders: one placed in the center of the culvert, one at each side of the motorway above the culvert, and one at each side of the motorway at the stream about 50 m from the culvert. Furthermore, bat activity was monitored manually (detector + visual) by observers on each side of the culvert. The observers focused on the bats flying over the motorway. For each bat pass the flight height and direction were recorded and the species identified.
Culvert A was not effective in guiding 90% of any bat species safely underneath the motorway. 72% of *Myotis daubentonii* used the culvert, the remaining individuals either turned at the tunnel or flew across the motorway at low height. *Nyctalus noctula, Eptesicus serotinus, Pipistrellus nathusii* and *pygmaeus* and *Barbastella barbastellus* did not use the culvert and either crossed above the motorway or turned at the culvert. Culvert B, which was 1m higher than Culvert A, guided 97% of all *Myotis daubentonii* safely underneath the motorway. 8% of *Pipistrellus pipistrellus* used the culvert, while the remaining species (*Nyctalus noctula*, *Eptesicus serotinus* and *Pipistrellus pygmaeus*) either crossed above the motorway or turned at the culvert. A considerable proportion of the bats crossing above the motorway did so at unsafe heights; *Nyctalus noctula* most often crossed above traffic height, but hunting animals sometimes flew at unsafe heights.

A bat culvert in the Netherlands constructed for *Myotis daubentonii* was monitored in a controlled before-and-after study by Koelman (2009 & 2013). The culvert was built to safeguard a flying route between roosts in a park and foraging areas when the old waterway was filled in to make room for new buildings. The culvert is W 1.70 m, L 204 m , and the photos in the report indicate that the height above water is around 1 m. During construction, a temporal flying route was offered using fences.
The study site was monitored during 2006, 2007, 2009, and 2010 with varying effort. Bats exiting the culvert were counted using acoustic detection and direct observation. Additionally, an automatic ultrasound recorder was placed inside the culvert. Bat activity above the culvert was monitored, though not as frequently as the automatic recorders were used.

Before construction, in 2006 and 2007, 27 and 14-19 animals, respectively, used the now destroyed route. In 2009, three animals used the culvert and in 2010, four animals used it. The culvert functioned as a flight path as well as a forage site. The bats registered above the culvert flew from the colonies to the hunting grounds in a more or less straight line, unusually high above a building; 7 animals in 2009 and 14 animals in 2010.

Abbott et al. (2012a) made a replicated, site comparison and controlled study in 2008 at 25 under- and over-structures on a motorway in agricultural and woodland habitats in Ireland. Bat activity was recorded acoustically on two nights at five viaduct bridges across rivers, one boxed shaped culvert, seven road tunnel underpasses carrying minor roads, six road overbridges and six severed treelines. None of the structures were constructed as wildlife crossings. Bat activity was recorded above and in the underpasses, and in the adjacent habitat simultaneously as controls. Bats (*Pipistrellus pipistrellus, Pipistrellus pygmaeus* and *Myotis* sp.) used under-motorway routes, particularly river bridges, more than over-motorway routes. *Rhinolophus hipposideros* was only recorded crossing beneath the motorway under river bridges and via road tunnels. 6.4% of bat passes at tunnels carrying roads were recorded above motorway level. At the culvert 46.4% of the total bat passes (excluding *N. leisleri*) were detected over, rather than inside the culvert. The culvert had a low clearance height (~1.75 m) above the water surface, and the remaining tree canopies on either side extended well above the level of the motorway. *Nyctalus leisleri* always flew over the road-tunnels and the culvert.

In a controlled, site comparison study, Abbott et al. (2012b) examined whether inter-species differences in flight capability and sensory perception would influence bat use of potential underpasses. Bat activity in two narrow drainage culverts (<1.5 m in diameter, and L 43 m and 91 m, respectively) under a motorway were compared to bat activity in a nearby road underpass tunnel (H 6 m, W 16.6 m, L 26 m) under the motorway. All-night acoustic monitoring was undertaken 17-18 times during May-September 2009 and 2010 in each of the three road underpasses using automatic ultrasound recorders. Furthermore, to test whether bats crossed the motorway above the underpass, simultaneous recordings were made above and below the underpass during the 16 nights in May 2009. Bat activity in the vicinity of the motorway was recorded as a control. Statistical tests were used to evaluate inter-species differences in flight path selection above or inside the underpass.
Bat activity inside the underpass indicated clear guild-specific responses to the passages' dimensions. Only *Rhinolophus hipposideros, Myotis nattereri* and *Plecotus auritus* flew through the narrow drainage culverts. These species are adapted for flight and foraging in cluttered airspace. Both culverts were used regularly as flyways by *Rhinolophus hipposideros* and *M. nattereri*. Edge-space foraging species (*Pipistrellus pipistrellus, Pipistrellus pygmaeus*) were highly active in the area but never flew through the narrow culverts. All species, except the open-air hunting *Nyctalus leisleri*, flew through the large underpass. Simultaneous recordings made above and in this underpass indicated that species' tendency to cross over rather than using the structure was inversely related to the degree of clutter-adaptation. The authors conclude that if the target species for mitigation are clutter-adapted bats, their findings indicate that incorporation of a greater number of suitably located small tunnels into new roads may facilitate safe passage more effectively than fewer large underpasses.

Berthinussen & Altringham (2012) made a controlled, replicated site comparison study of the effectiveness of gantries and underpasses compared to sites with no mitigation measures. Two tunnels and a culvert carrying a small stream were investigated at a dual carriageway in the UK. Underpass A (H 3 m, W 6 m, L 30 m) carried a wide footpath beneath the road. It was located near a known commuting route, but trees and shrubs were planted along 200 m

of the road in an attempt to divert bats from the unmitigated commuting route. Underpass B (H 5 m, W 6 m, L 30 m) was built to carry a hedgerow-lined minor road under the carriageway. The hedgerow was a known bat commuting route. The culvert was dimensioned H 2.5 m, W 5 m, L 15 m. Echolocation calls and observations were used to determine the number of bats using underpasses in preference to crossing the road above, and the height at which bats crossed.
Underpass B was determined to be effective as 96% of the bats used the underpass to cross safely under the carriageway. Activity levels were higher at this underpass than at underpass A and C. The other two underpasses (a tunnel and a culvert) were determined to be ineffective as crossing sites for bats, as most bats crossed the carriageway at the height of passing vehicles. The authors conclude that this was probably because these two underpasses required the bats to change their flight routes and flight height. The ineffective underpasses also had smaller cross-sectional areas than the effective underpass B. Bats species registered in the underpasses were *Pipistrellus pipistrellus, Pipistrellus pygmaeus* and *Myotis sp*. These species were also detected flying over the road at all three underpasses (except *P. pygmaeus* at underpass A). Furthermore, *Plecotus auritus* was registered flying across the road above underpass A.

In a descriptive, partly controlled study by Brekelmans et al. (2011), three underpasses (a small culvert, a road tunnel and a railway tunnel) under a motorway in the Netherlands were monitored. Dimensions of the underpasses were not stated. The monitoring took place during three visits where bat activity in the underpasses was examined by acoustic and visual observation or using an automatic ultrasound recorder. During one of these visits, bat activity at the road verge was also registered. Both the tunnel and the culvert were used by a large number of *Myotis daubentonii*, the former also by *Pipistrellus pipistrellus*. With only two observations of *Pipistrellus pipistrellus*, the railway tunnel was hardly used. Only *Nyctalus noctula* was observed at the road verge flying across the road.

In a replicated study, Boonman (2011) compared culverts (carrying canals, streams or drains) with different dimensions in relation to how much they were used by bats. The proportion of bats flying over the roads/railways instead of through the culvert was not examined. 54 culverts used by bats were each examined for one night. Bat passes were registered inside the culverts and in front of one end of each culvert.
Bats were recorded in all culverts, except the smallest ones (8 culverts, cross sectional area <4 m^2). *Nyctalus noctula* was never registered inside culverts. *Eptesicus serotinus* were only recorded inside three very large culverts though both species were present at 21 and 31 locations, respectively. *Myotis daubentonii, Myotis dasycneme*, and *Pipistrellus pipistrellus* were regularly recorded inside the culverts. Culvert length and additional guidance (eg. hedges) were not significant in explaining the use of culverts by any of the three species. Cross sectional area was a significant factor for all three species, as well as for *Myotis dasycneme*. Height was the most important component of the cross sectional area for *Myotis daubentonii* and *Pipistrellus pipistrellus*. The author estimated minimum cross-sectional area for three species based on a 95% probability that a culvert is used: 7m^2 for *Myotis daubentonii*, 18m^2 for *Myotis dasycneme*, and 47m^2 for *Pipistrellus pipistrellus*.

Kerth & Melber (2009) compared the effect of a motorway on *Barbastella barbastellus* and *Myotis bechsteinii* in a German forest. The motorway had 4-5 lanes creating a 30-40 m wide gap in the tree vegetation. Traffic intensity during day and night was very high. The study examined the use of three road underpasses (A, B, and C) which pass under the motorway in the study area (H ~4.5 m, W ~10m (A), and 5 m (B and C), L ~30 m). The B-tunnel is located within the forest and the other two (A and C) at forest edges. A public road with heavy traffic leads through tunnel A, whereas small gravel roads lead through B and C. Six female *B. barbastellus* and 34 female *M. bechsteinii* were radiotracked. Mist netting was carried out in tunnels B and C as well as at 10 other sites along flight paths in the forest. The following species were captured in considerable numbers in tunnel B and C: *Barbastella barbastellus, Myotis bechsteinii, Myotis myotis, Myotis nattereri,* and *Plecotus auritus*. Only *Barbastella barbastellus* and *Myotis nattereri* were caught significantly more often in the tunnels than at the forest sites. Five out of six radio-tracked *Barbastella barbastellus* crossed the motorway during foraging and roost switching, flying through underpasses or directly over the motorway. In contrast, only three of 34 radio-tracked *Myotis bechsteinii* crossed the motorway during foraging trips, all three using an underpass. *Myotis bechsteinii*, unlike *Barbastella barbastellus*, never crossed the motorway during roost switching.

A site comparative study monitored the success of mitigation measures, primarily two tunnels, installed at a new road scheme in Wales, United Kingdom (Wray et al. 2006). The tunnels were built as a bat mitigation measure. The road improvement scheme comprised a single carriageway, severing the foraging habitat and commuting routes for *Rhinolophus ferrumequinum*. Mitigation also included enhancement of hedgerows and treelines as commuting routes away from the road, degradation of habitats adjacent to the road and adaptations of street lights at crossing sites. Baseline surveys involved two surveyors with bat detectors at 12 potential crossing points on at least two occasions during the summer at the start of construction in 2001. Bat road casualty searches were also conducted. Following the baseline survey, two tunnels providing safe crossing points under the road were installed to increase the permeability. The tunnels were aligned with existing flight lines. Bats were monitored again in 2002 and 2003 after the road and mitigation construction, presumably in the same manner as the baseline surveys. The two tunnels were monitored by placing an automatic bat recorder in each of them. No simultaneous monitoring in and above the culvert was reported.
Rhinolophus ferrumequinum was recorded using each bat tunnel on only one occasion in 2002 and 2003, respectively. In 2004 a single survey recorded *Rhinolophus ferrumequinum* passes in one of the tunnels, and the authors report that their use is increasing. The tunnels were well used by *Myotis sp.* and *Pipistrellus* sp., both for commuting and occasionally for foraging. No bat road casualties were recorded on any of the eight visits, neither on the existing road during baseline surveys nor on the improved road when it had opened.

Bach et al. (2004) extracted data from investigations in Würzburg and Hessen, Germany, and gathered unsystematic data from various German EIAs describing bats' use of tunnels, culverts and wildlife overpasses. In Würzburg and Hessen, 12 under-motorway tunnels were studied using ultrasound detectors and visual observation, or automatic ultrasound recorders alone. All tunnels connected forests or farmland hedgerows to villages or forests. In the EIAs, 9 tunnels were checked to determine if they were used by bats. Bat activity above the underpasses was not surveyed in any of the studies.
In Würzburg 6-7 species were observed commuting through the tunnels (H 4 m, W 4.5 m, L 31 m); *Myotis brandtii/mystacinus* were most frequent, followed by *Barbastella barbastellus, Myotis bechsteinii, Myotis nattereri*, and *Pipistrellus pipistrellus*. One *Nyctalus noctula* was also registered. Furthermore *Plecotus auritus/austriacus* was observed hunting in the tunnels. In Hessen, four bat species were observed commuting through the tunnels (H 5 m, W 4 m, L 45 m). Again, *Myotis brandtii/mystacinus* was observed most frequently, followed by *Pipistrellus pipistrellus, Myotis myotis* and *Myotis nattereri*. These tunnels were also used for hunting by 6-8 bat species, most commonly *Myotis brandtii/mystacinus,* but also *Myotis bechsteinii, Pipistrellus pipistrellus, Barbastella barbastellus, Myotis nattereri* and *Plecotus auritus/austriacus*. In one of the pre-construction surveys, a relatively narrow culvert carrying a stream (H 2 m, W 1.5 m, L 30 m) was used by about 40 of the 45 bats in a nearby *Myotis nattereri* maternity roost. In contrast, the larger *Myotis myotis* was only observed frequently in larger tunnels with a height of at least 3.5 m.

Fuhrmann & Kiefer (1996) conducted a 2-year experimental study in order to find methods to prevent road mortality of *Myotis myotis* as a new road was planned on the top of a former railway embankment directly in front of the old station building containing around 220 roosting females. Flight paths of "undisturbed bats" were registered during the first year (1991) using bat detectors and night vision scopes. During the winter 1991/1992, an 80 m long and 4 – 5 m high construction was erected in front of the station building in the main flight path of the bats. During 1992, it was modified to simulate an underpass and a bridge, and the resulting flight paths of the colony were registered during three experimental setups: 1) an 8m wide gap was formed in the construction for the bats to fly through. No guiding walls were leading to the gap 2) underpass simulation: an 8m wide gap in the lower part of the construction (0 – 2.3 m above the ground) with guiding walls leading from the roost building to the gap, 3) bridge simulation: an 8 m or 16m wide gap in the upper part of the construction (2.3 – 4-5 m above the ground), guiding walls leading from the roost building to the gap. The results were not statistically analysed.
Without modifications (baseline, 1991): more than 80% of the registered bats flew low over the railway embankment as they emerged in the evening. The experimental construction was used by the bats in the following ways: 1) in April, 3% of the registered bats passed through the gap. In July, the amount had risen to 48%, 2) the simulated underpass was used by up to 65% of the registered bats, 3) the simulated bridge was used by up to 87% of the registered bats; the best results were obtained with a 16m wide gap (as opposed to 8m). The guiding walls seemed to be crucial to make the bats use of the experimental construction.

In a study of foraging areas and foraging behaviour of *Myotis emarginatus,* six adult individuals from a church attic nursery colony were radio tracked (Krull et al. 1991). The bats crossed a busy motorway 300 m from the colony through two tunnels instead of flying over the motorway straight towards the forest hunting grounds even though particularly one of the tunnels required bats to accept a larger detour. The dimensions of the two tunnels were not given.

Assessment and recommendations

We found 17 studies exploring bats' use of more than 120 tunnels or culverts. Less than 10 of those were constructed to facilitate bat crossings of large roads. Almost half of the studies were controlled, examining the different extents of bat activity across the road above the underpasses, as well as in the tunnels or culverts. The remaining studies only measured bat activity inside the underpasses, compared underpass use to the use of other mitigation measures, or were radiotracking studies. Many studies found variations (some statistically significant) in the bats' use of the underpasses depending on the species' flight behaviour and the dimensions of the underpass.

Two studies comparing different kinds of mitigation measures found underpasses (particularly river bridges and culverts carrying waterways) to be most used by bats (Abbott et al. 2012a, Cichocki 2015). Incidental information suggests that bats in some cases will change their flight routes in order to use an underpass (Krull et al. 1991), while other studies have not recorded that behaviour.

Collectively, the studies report at least 18 species detected in tunnels or culverts of differing dimensions: *Rhinolophus ferrumequinum*, *Rhinolophus hipposideros, Myotis emarginatus, Myotis bechsteinii, Myotis brandtii/mystacinus, Myotis daubentonii, Myotis dasycneme, Myotis myotis, Myotis nattereri, Myotis escalerai, Plecotus auritus, Plecotus austriacus*, *Barbastella barbastellus, Pipistrellus pipistrellus, Pipistrellus pygmaeus, Pipistrellus kuhlii, Rhinolophus mehelyi/euryale*, *Eptesicus serotinus, and Eptesicus serotinus/isabellinus.*

Furthermore, there were single reports of *Nyctalus noctula* and *Nyctalus leisleri* from underpasses.

Individuals of manoeuvrable, low-flying species (group A and B) were observed in underpasses in all studies that accounted for species registrations in detail. They were observed in both large, but also in narrow underpasses, where higher-flying and less maneouvrable species were not registered.
Extremely manoeuvrable species in particular, including *Rhinolophus hipposideros, Myotis emarginatus, Myotis bechsteinii, Myotis nattereri, Plecotus auritus* and *Plecotus austriacus,* were registered in tunnels or culverts with small cross-sectional areas. Two narrow drainage pipes (< 2 m high) were used by *Rhinolophus hipposideros* and *Myotis nattereri* and to some extent by *Plecotus auritus* (Abbott 2012b). A narrow culvert (H 2 m, W 1.5 m) even proved quite effective for a nearby *Myotis nattereri* maternity roost and was used by about 88% of the individuals (Bach et al. 2004). However, another study did not find any bat activity in any of eight culverts which had a cross sectional areas <4 m^2 (Boonman 2011). Local conditions may play a role in determining if the tunnels or culverts are used or not e.g. if the underpass is placed on an existing commuting route, and whether it requires bat to alter their flight height and direction.

Relatively low-flying species such as *Rhinolophus ferrumequinum, Rhinolophus mehelyi/euryale, Myotis brandtii/mystacinus, Myotis myotis, Myotis daubentonii,Myotis dasycneme,* and *Myotis escalerai* seem to vary somewhat regarding which underpass size they will use. *Myotis daubentonii* are often registered in narrow culverts, and a H 2.4 m, W 5.6 m, L 30 m culvert guided 97% of *Myotis daubentonii* underneath a motorway (Møller et al. 2014). However, an extremely narrow culvert carrying a stream (height ca. 1 m, width 1.7 m, length 204 m) and placed on a *Myotis daubentonii* flight route was only used by 4 of 18 bats 2 years after construction (Koelman 2009 & 2013). Boonman (2011) recommended a minimum cross sectional area (based on a 95% probability that a culvert is used) of: 7m^2 for *Myotis daubentonii*, and 18m^2 for *Myotis dasycneme*. Like *Myotis dasycneme*, *Myotis myotis* also seem to require tunnels with a larger cross sectional area, and studies report this species from tunnels with a height of 3.5 m or more (Bach et al. 2004, Kerth & Melber 2009). An experimental underpass (H 2.3 m, W 8 m) was only used by up to 65% of observed *Myotis myotis* individuals from an adjacent colony (Fuhrmann & Kiefer 1996). *Myotis brandtii/mystacinus* was found to use tunnels with height and width of 2.5 m or more (Berthinussen and Altringham 2015, Bach et al. 2004).

Bats with medium manoeuvrability, namely *Pipistrellus* sp. were registered in tunnels and culverts in the majority of studies (Abbott et al. 2012a, 2012b, Bach et al. 2004, Barros 2014, Berthinussen & Altringham 2012, 2015, Boonman 2011, Brekelmans et al. 2011, Naturalia Environnement & FRAPNA 2015, Wray et al. 2006). The smallest entrance size registered in tunnels used by *Pipistrellus sp.* was 2.5 m height and 2.5 m width (Berthinussen & Altringham 2015). A tunnel with the dimensions H 4.5 m, W 4.5 m, L 45 m was used by 96% *Pipistrellus pygmaeus* and 93% *Pipistrellus pipistrellus* and thus seemed to be efficient for those species. However, based on bat registrations in 54 tunnels, Boonman (2011) concluded that the minimum cross sectional area for *Pipistrellus pipistrellus* (based on a 95% probability that a culvert is used) is 47 m^2.

Medium-manoeuvrable species such as *Eptesicus* sp. and *Barbastella barbastellus* (group D), which display a more straight flight pattern than bats in category C, were registered flying through tunnels in three studies (Barros 2014, Boonman 2011, Kerth & Melber 2009). The tunnels in all studies were large. The exact measurements were only given in one of the studies (H 4.5 m, W 5 m, L 30 m); in one of the other studies the average dimensions of all tunnels were 4.25 m high and 9 m wide.

Less manoeuvrable bats, which most often fly high and straight in the open airspace, e.g. *Nyctalus leisleri* and *Nyctalus noctula* (group E) were generally not found using tunnels or culverts (Abbott et al. 2012a, 2012b, Brekelmans et al. 2011, Boonman 2011). However, two studies report of *Nyctalus noctula* and *Nyctalus leisleri* using tunnels (Bach et al. 2004, Barros 2014). The observations are not described in detail, and the studies use automatic ultrasound recorders placed inside the tunnels as one of the primary registration methods. Therefore, it seems possible that the registrations could be artefact recordings of the loud ultrasound calls from individuals of these species passing *outside* the tunnels. Whether or not this is the case, the reviewed studies clearly show that less manoeuvrable, high-flying species generally do not use tunnels and culverts.

In conclusion, the 17 studies show that tunnels and culverts can be used as crossing structures by most bats except the less manoeuvrable, high-flyingspecies in group E. However, only three studies could provide evidence that underpasses were effective in helping at least 90% of bats safely beneath the road. The cross sectional areal of the underpasses – particularly the height – is a significant factor in determining which species use the underpass, and how efficient it is (Abbott et al. 2012a and 2012b, Berthinussen & Altringham 2015, Boonman 2011, Møller et al. 2014). The location of the underpass is another significant factor: Underpasses placed on bat commuting routes that do not require bats to change their course and flight height seemed to be more effective (Berthinussen & Altringham 2012, 2015).

Culverts seem to be more effective than tunnels (Cichocki 2015, Naturalia Environnement & FRAPNA 2015), possibly because the waterways function as commuting routes for many smaller low-flying bat species. Culvert length or additional guidance (e.g. hedges) was not significant in explaining the use of culverts carrying waterways (*Myotis daubentonii, Myotis dasycneme*, and *Pipistrellus pipistrellus*, Boonman 2011). However, it is likely that hedges and tree rows play a significant role in enhancing the use of tunnels, where there is no waterways guiding the bats.

We find culverts and tunnels to be a very promising mitigation measure, but there is at present not enough data to determine which minimum dimensions are necessary to ensure that the underpasses are effective for each bat species. Further research regarding functional dimensions is needed before underpasses can be confidently applied to road mitigation strategies. In many of the reviewed studies, vital information such as tunnel or culvert dimensions, whether underpasses carried roads or waterbodies, and how the underpass was connected to the surrounding habitat, was missing. Furthermore, many studies exclusively recorded the number of bat passes and bat activity inside the underpasses. More comprehensive experiments and a more detailed description of the study area, conditions and procedures are needed to obtain the detailed information needed on the variables (particularly dimensions) determining underpass effectivity.

3.2.2 Viaducts and river bridges

Viaducts are elevated bridges that carry road infrastructures across valleys or low-lying areas (Iuell et al. 2003). Viaduct bridges are often not constructed to mitigate road effects on wildlife species, but they may function as large underpasses due to size, clearance and structure. The passage under the viaducts may preserve existing wildlife corridors and habitats in the landscape.

Summaries

Abbott et al. (2012a) made a replicated, site comparison and controlled study in 2008 at 25 under- and overcrossing structures on a motorway in agricultural and woodland habitat in Ireland. Bat activity was recorded acoustically on two nights at five viaduct bridges across rivers, one boxed shaped culvert, seven road tunnel underpasses, six road overbridges and six severed treelines level or above road height. None of the structures were constructed as wildlife crossings. Bat activity was recorded above and below the motorway structures and in the adjacent habitat simultaneously. Bats (*Pipistrellus pipistrellus, Pipistrellus pygmaeus* and *Myotis sp*.) used under-motorway routes, particularly river bridges, more than over-motorway routes. *Rhinolophus hipposideros* was only recorded crossing the motorway under river bridges and road tunnels. 2% and 6.4% of bat passes at river bridges and underpasses, respectively, were recorded above motorway level.

Assessment and recommendations

The reviewed literature on underpasses in general indicates that spacious underpasses are used by more species and individuals. In the one study we found on river bridges, they were effective in helping 98% of bats (*Pipistrellus pipistrellus, Pipistrellus pygmaeus* and *Myotis* spp.) cross safely under roads. The fact that viaducts are usually constructed above natural guiding structures such as waterways or valleys increases chances that bats will use them. We recommend that whenever possible, viaducts should be constructed instead of tunnels and culverts.
Considerations should be given to the collision risk for open-airspace hunting species which may fly low across the elevated road stretch on the viaduct bridge.

3.3 Speed reduction

Vehicle speed is a major determinant of the risk of vehicle collisions for multiple vertebrate taxa (DeVault et al. 2015, Farmer & Brooks 2012). As vertebrate road mortality increase with speed, speed reduction could be an effective method to reduce bat road mortality risk and mitigate the effects of roads.

Summaries

A Spanish study analysed data of road-killed bats collected during 1998 and 1999 on 421 km roads (Bafaluy 2000). The posted speed limit ranged from 50 to 100 km/h, but it was 80 and 90 km/h on most of the surveyed roads. Traffic intensity was low to medium on the surveyed roads. 42 bats representing 12 species were collected.
Factors determining road mortality were; bat species, habitat, season of the year, and posted speed limits. *Pipistrellus pipistrellus* and *Pipistrellus kuhlii*, two anthropophilic species, constituted 71 % of the total recorded bat mortalities. Higher mortality was observed during the post reproduction period and on roads near towns. The authors listed how many road-killed bats were found on roads with different posted speed limits: 50 km/h: 6 carcasses, 80 km/h: 16 carcasses, 90 km/h: 6 carcasses, 100 km/h: 14 carcasses. However, the authors did not relate the number of carcasses to the length of road stretch searched within each speed category, nor for species or habitat variables. As most roads in the study have speed limits of 80 or 90 km/h, the mortality figures are biased.

Assessment and recommendations

We found one study examining the relation between bat mortality and posted speed limit on roads. Despite of the biased mortality figures, there was some indication that vehicle speed and bat mortality was correlated but the study did not provide reliable evidence, and the sample size was small. There are no studies documenting a correlation between bat road mortality and vehicle speed. However, it is likely that the two factors are related as they are for other groups of vertebrates (Farmer & Brooks 2012). Capo et al. (2006) observed that mortality declined on a section located at an approach ramp of a new interchange on a ring road near Bourges in France. The authors attributed the decreased mortality to a decrease in vehicle speed.

Speed reduction could potentially be a simple and effective method to reduce mortality risk for bats without compromising road permeability. Speed reduction have the advantage that it can be used on road stretches where flight routes across the road are dispersed, e.g. in forest areas and open foraging habitats with no distinctive landscape features. Furthermore, it is likely to be effective for most bat species, although bat echolocation range could be a parameter causing species-specific variability to the effectiveness of the measure. Reduced speed limits could be restricted to the hours from sunset to sunrise, when traffic intensity is low, thus not reducing road permeability for vehicles. However, speed reduction may only be applicable on smaller roads.

With the present level of evidence, speed reduction cannot be recommended as a mitigation measure. There is a need for species-specific studies to elucidate the relationship between vehicle speed and mortality risk in relation to factors such as topographic and habitat variables. Reduced mortality rates at road sections with lowered speed should be verified, e.g. by site comparative mortality studies or by applying predictive modelling to mortality studies to estimate the effectiveness of a speed reduction.

3.4 Deterrence and diversion

Mitigation measures deterring or diverting bats away from the road aim to reduce the number of vehicle collisions. As these measures may also increase the barrier effect of the infrastructure, they should only be used in combination with measures that provide safe crossing sites for the bats.
Interventions to deter and divert bats may include artificial light and barrier screens to deter the bats and fences, treelines and hedgerows to divert the bats away from the road. Noise barrier screens installed to reduce adverse effects of noise on humans will inadvertently function as barriers or guidance structures for bats.
Degradation of potential foraging habitat on the road verges and adjacent to the road as well as adaptations of streetlight to reduce insect aggregations have also been suggested as potential measures to reduce mortality risk for bats (Wray et al. 2006, T. Kokurewicz, pers. comm.).

3.4.1 Light

Artificial lighting may disturb bats and cause strong avoidance behaviour by some bat species (Stone et al. 2015, Rowse et al. 2016). The photosensitivity of bats is species-specific and varies with light intensity and spectral content. Particularly slow-flying manoeuvrable species such as *Myotis* sp., *Rhinolophus* sp. and *Plecotus* sp. avoid street lights and are very sensitive to artificial light in their habitats and commuting routes (Brinkmann et al. 2008, Kuijper et al. 2008, Stone et al. 2009). Other species, e.g. *Pipistrellus* sp. and *Eptesicus* sp., seem less sensitive to lights and often forage on insects around street lights (Rydell 1992, Blake et al. 1994, Rydell & Baagøe 1996).

Strong lights have been employed as a mitigation measure to reduce road mortality for bats. If lights are placed strategically on the road verges, they may deter the bats from attempting to cross the road and divert the bats to safer crossing points (Wray et al. 2006, Billington 2013).

Amber coloured narrowband LED street lighting, which should be less visible and hence more tolerable to bats than normal wideband white street lighting (Fure 2012, Rowse et al. 2016), have also been installed as mitigation to reduce the impact of light pollution from roads (V. Loehr pers. comm.). Furthermore, amber coloured light does not attract as many insects and thus foraging bats as white light does (Blake et al. 1994).

Summaries

Various mitigation measures (culverts, fencing, planting and regular trimming of vegetation, panels on footbridge, light deterrence and enhancements of roosting sites) were installed to help *Rhinolophus hipposideros,* in particular, to safely cross an upgraded main road in order to maintain a population in Wales, United Kingdom (Billington 2013, Picard 2014). The effects were assessed in a before-and-after study encorporating nursery roost counts. Low-level bollard lights were installed near the road margins to divert bats to a river bridge. The bollard lighting was reported as being very successful in both preventing bats from crossing the road, and at times directing up to at least 176 *Rhinolophus hipposideros* each night beneath the river bridge. The route under the bridge did not appear to be used by bats before the lights were installed.

The aversive effects of light on *Myotis dasycneme* were experimentally studied by placing a strong lamp (1000 W) along existing commuting routes (Kuijper et al. 2008). Each experimental site had specific characteristics, which allowed exploration of the interacting effects of light disturbance and the environment.
The lamp was placed on the banks of canals known to be commuting routes for pond bats. The number of passing bats, the percentage of feeding buzzes relative to total commuting calls and flight patterns were compared between dark control nights and experimentally illuminated nights. In experiment 1, the lights were placed perpendicular to a flight path to investigate if bats would use a known alternative route. Experimental light was applied over four nights, and there were correspondingly four unlit control nights. In experiment 2, the effect of light applied perpendicular to the flight route was examined during one illuminated night and two dark control nights. In experiment 3, the light was pointing against the flight direction of the bats. Two different test sites were used with one illuminated night and two dark control nights at each site. The results were statistically tested.
There were no clear effects of experimental light on the number of passing bats, nor did more bats use an alternative commuting route when just one of two possible routes was lit. However, light did reduce the percentage of feeding buzzes by more than 60%, although the abundance of insect food tended to increase. Light disturbed the flight patterns of *Myotis dasycneme*. When approaching the beam of light, between 28% and 42% turned before continuing on their normal commuting route. Virtually all *Myotis dasycneme* (96%) turned when the light was erected on an existing barrier and they had to fly straight into the beam of light. These disturbing effects also seemed to occur at low levels of light intensity. The authors point out that it is unclear how long-term exposure of light along a commuting route will affect the behaviour of bats. It could lead to the use of an alternative commuting route or to a habituation to the new situation.

An un-controlled, descriptive study monitored the success of mitigation measures, primarily two tunnels, installed at a new road scheme in Wales, UK (Wray et al. 2006). During the study period, an existing culvert carrying a stream was partially lit up by new street lights near the entrance to the culvert. The bats (species not specified) that were observed using the culvert before the lights were installed appeared to modify their behaviour in response to the lighting by hesitating before flying faster and lower through lit areas.

Currently, a number of studies focussing on LED-lighting in multifunctional passages (experiments including different light spectra and restricted lighting) and the effects on bat activity and use of culverts or tunnels, are being carried out in the Netherlands, but no results are available yet.

Assessment and recommendations

There are numerous studies of bat behaviour in relation to different types of street lighting (e.g. Rydell 1992, Blake et al. 1994, Rydell & Baagøe 1996, Stone et al. 2015, Rowse et al. 2016). Only two studies, which used used light as a deterrent to stop bats crossing roads at dangerous places, were identified. White light seemed to be successful in redirecting a large number of *Rhinolophus hipposideros* to a safe crossing point beneath a river bridge (Billington 2013). Light also affected the flight patterns of *Myotis dasycneme* and *Myotis daubentonii* (Kuijper et al. 2008, Wray et al. 2006). This is consistent with previous studies showing that *Rhinolophus* sp., *Myotis* sp. and *Plecotus* sp. avoid light (e.g. Stone et al. 2009, Rowse et al. 2016).

Even though one of the studies strongly indicated that light bollards were effective in redirecting *Rhinolophus hipposideros,* long term studies are needed to determine the effectiveness of light at species level, and whether bats habituate to the light. Furthermore, collateral effects of installing deterring lights need to be examined, e.g. to what extent species that hunt near street lamps are attracted to light bollards, and if the lights increase the barrier effect of the road. The latter can be assessed by monitoring the proportion of bats that are not guided to a safe crossing point by light but are only deterred from crossing the road.

3.4.2 Noise

Traffic noise reduces foraging efficiency for many bat species (Schaub et al. 2008, Siemers & Schaub 2010, Luo et al. 2015, Bunkley & Barber 2015). The noise does not mask prey echoes but may increase the search time required for a successful prey capture by gleaning bats (Bunkley & Barber 2015). Traffic noise seems to act as a general aversive stimulus that causes an avoidance response (Zurcher et al. 2010). Noise may be used in an effort to try to deter bats from crossing the road at a particularly dangerous site.

Summaries

A LIFE project carried out in Provence, France, aimed, among other things, to provide innovative and effective tools to help *Rhinolophus ferrumequinum* and *Myotis emarginatus* safely across infrastructure (ChiroMed 2014). The project tested two types of mitigation measures: Applying noise-generating road coating to specific road stretches, and installing a bat corridor on an over-bridge carrying a two-lane road. *Rhinolophus ferrumequinum* typically cross open stretches, such as roads, at very low altitudes. The special road coating generates a powerful noise at frequencies audible for the bats, when a vehicle passes. The aim is to warn bats of an approaching vehicle, to cause an aversive response and thus reduce mortality rates. Direct observations with thermographic cameras were conducted in the summer of 2011 before the road surface had been modified, and in the summer of 2013 after the road noise generating surface had been installed.
In 2011, 74% of bats crossed the road and only 2% aborted the crossing. In 2013, after the road surface had been altered, 65% of bats crossed the road directly and 22% aborted the

crossing attempt. When a car was present, 50% of the bats aborted attempts to cross the road and 38% crossed the road, compared to 12% and 75% when no car was present. 47% of the bats crossed the road directly and 40% turned back when a vehicle was outside of the band of noise generated by the road surface against 27% crossing directly and 64% aborted the crossing when a vehicle was driving on the special road surface band.

In a descriptive study from Indiana, USA (Zurcher et al. 2010) observed flight patterns of bats at flight paths intersected by roads. 211 cases of bats approaching the roads were observed, and bat behaviour at the intersection was registered. Telemetry data was used to identify where roads severed the commuting routes of bats (*Nycticeius humeralis, Myotis sodalis, Lasiurus borealis, Lasiurus cinereus, Eptesicus fuscus,* and *Perimyotis subflavus*). Five study sites were selected representing the most commonly used commuting routes. Bats were observed by means of night vision binoculars. Species identification was not attempted. The information recorded at each bat approach included: the presence or absence of vehicles, the flight height of the bat, whether a bat reversed course prior to crossing the road and if so the distance from the road or vehicle (if present) when it altered its direction, and finally the speed, type and relative level of noise emitted by vehicles.
Results showed that bats were more likely to reverse course when vehicles were present on the road. When automobiles were present, 60% of bats exhibited avoidance behaviour, reversing course at an average of 10m from a vehicle. Conversely, when no automobiles were present only 32% of bats reversed their course and 68% crossed the road. The flight height of the bats, vehicle speed, vehicle type or level of noise emitted by vehicles had no effect on the likelihood of bats reversing course. The authors conclude that the data support the hypothesis that bats perceive vehicles as a threat and display anti-predator avoidance behaviour in response to their presence.

Assessment and recommendations

We found one study that tested the use of noise as a deterrent on roads to reduce bat mortality risk. The observations suggest that *Rhinolophus ferrumequinum* altered their behaviour when vehicles drove on a road section coated with an audible warning surface (ChiroMed 2014). The effects of audible deterrence on bat behaviour at roads were tested at this one site. It has subsequently been installed at a second site in France but the effectiveness has yet to be evaluated (ChiroMed 2014).

The measure has the advantage that it can be used on road stretches where flight routes are dispersed, e.g. in forest areas and open foraging habitats with no distinctive landscape features. However, the measure may not be effective on roads with dense traffic where animals are continuously disturbed. The applicability may also be limited at roads with fast traffic, and dependent on the frequencies generated by the vehicles crossing the asphalt, and bat species involved. Due to these limitations, the audible warning road surfaces may only be used on roads with non-continuous traffic and with a speed limit of less than 100 km/h (ChiroMed 2014).

Before further assessments, noise deterrence must be tested at more sites to confirm the aversive behavioural response by *Rhinolophus ferrumequinum* and other species. Further studies are needed to verify the potentially reduced mortality rate and to examine if the connectivity of commuting routes is maintained. Long-term monitoring studies should also evaluate the potential habituation of bats to the noise stimuli.

3.4.3 Hedgerows, treelines and fences

Most bat species orientate themselves to some extent by means of landscape structures such as hedgerows, treelines, rivers or streams and forest edges (e.g. Limpens & Kapteyn

1991). Fences, treelines, and hedgerows are often installed or planted to divert bats away from unsafe crossing sites or to connect existing bat flight routes and foraging habitats to safe crossing sites (e.g. Limpens et al. 2005, Billington 2013). Barrier screens and fences can also be installed to discourage bats from crossing the road at sections over an underpass or at road sections adjacent to other safe crossing points.

Summaries

In a replicated, controlled, site comparative study, Cichocki and co-workers (Cichocki 2015) monitored bat activity at gantries, underpasses for large mammals and watercourses, wildlife overpasses constructed for large mammals, and road underpasses and overbridges of a motorway in an agricultural and forested landscape in Poland. Screens were erected on the road verges above all culverts and at one of the three gantries. Bat activity was recorded once a week in March-November from 2012 to 2014 at the gantries and along 250 m motorway sections on each side of the gantries from sunset to sunrise using ultrasound detectors, infrared cameras and visual observation. Simultaneously, road-kills were recorded once a week to identify potential conflict sites. Only a few fatalities were recorded (n=25). Most of these were *Nyctalus* and *Pipistrellus* bats.

Mitigation measures (culverts, fencing, planting and regular trimming of vegetation, earth ramps, light deterrence and enhancements of roosting sites) were installed to help particularly *Rhinolophus hipposideros* safely cross an upgraded main road and maintain the population in Wales, United Kingdom (Billington 2013, Picard 2014). The effects were assessed in a before-and-after study and nursery roost counts. Bat activity, roost size, flight paths, road crossing points etc. was monitored by means of bat surveys, road casualty surveys, radio-tracking surveys and roost counts. In 1997-2000 (prior to the road opened), roost counts, flight routes and feeding area surveys were carried out. After the road opened in 2001, roost counts were continued, and bat casualty surveys as well as identification of road crossing points and flight paths were carried out regularly (but not each year) during 2001-2013, as mitigation measures were added and optimized.
The study found evidence that bats were guided by vertical walls at culverts prevented bats from flying over the road, by fences and trees created a funnelling effect towards a culvert or bridge and; planting improved the integrity of flight corridors.

In a controlled, site comparative study Lüttmann (2012, 2013) compared road stretches with and without screens as bat mitigation. The five study sites consisted of two road stretches (a two-lane road and a four-lane motorway) with screens, a four-lane road with screens including a screen in the central reservation, a four-lane motorway without screens or other mitigation, and a 2-lane road with trees forming a natural hop-over. Each site was examined for at least 15 nights using bat detectors combined with infrared spotlights and cameras. Flight altitude of *Myotis* and *Pipistrellus* bats crossing the road was significantly higher in road sections with screens than in sections without fences. The screens also caused an increased movement of bats along the fenced road stretches (*Myotis* ≥ 40 %, *Plecotus* ≥ 70 % of all sites with screens). Screens represent barriers that prevent low-flying bat species (moderately structurally bound species like the *Myotis myotis*, *Myotis mystacinus /Myotis brandtii*) from entering the traffic area to some extent. However, *Pipistrellus* bats were also observed flying along the screens including the screen on the central reservation (Lüttmann, pers. comm.).

A motorway was constructed in southern Spain near a cave that is an important roosting site for bats, primarily *Miniopterus schreibersi* and *Myotis escalerai* (Almenar & Ciscar 2012). To reduce the mortality risk for bats arriving to and emerging from the roost and to reduce the disturbance for the roosting bats, a mitigation scheme was implemented. The mitigation

involved: three overpasses, two sections of wired mesh around the whole motorway between the overpasses, a wide road underpass, a viaduct bridge, planting and protection of vegetation, phonoabsorbant asphalt and noise barriers. A before-and-after study was performed to establish how the motorway affected the bats and how they responded to the mitigation measures (Almenar & Alcayde 2011, Almenar & Ciscar 2012). Ultrasound detectors and infrared video were used to monitor bat activity and behaviour. Furthermore, 30 individuals of different species were tagged with radiotransmitters. The roosting population was censused concurrently. At the time of the survey, some measures were only just finished or still in progress (mainly two of the overpasses).
The fieldwork showed that most of the animals did not cross the highway. Bat road crossings seemed to be positively correlated to the amount of vegetation near the road. Most road crossings occurred at 1/ the sections with screens, 2/ at the tunnel, and 3/ one of the overpasses. The road section with the wire mesh was not crossed.

A new high-speed railway in mountainous areas in southern Spain passed close by a cave housing more than 1000 bats of the genera *Rhinolophus, Miniopterus* and *Myotis.* Wire fences were established along the railway track to protect the roosting population from train collisions. The wire fences were 5 m high and ran 110 m on both sides of the railway track between two railway tunnels.
Flaquer et al. (2010) monitored the flight routes used by bats to cross the fenced section of the railway to evaluate the effectiveness of the mitigation measures. Bats were recorded using infrared video cameras and bat detectors. Numbers of roosting bats in the cave were known from pre-construction censuses and were monitored concurrently.
544 individual bats were registered crossing the railway. 61% crossed above the entrance to the railway tunnel close to the cave entrance and 40% crossed through a road underpass (8 m x 6.4 m) in the railway embankment. It seems that the wire fence was successful in preventing bat-train-collisions. Most bats approaching the wire fences crossed over them or flew parallel to them. Less than 5% of the bats flew down between the fences over the railway and thus, were at risk of collisions with trains. The number of roosting bats increased during the construction and monitoring period. Species-specific data was not provided.

In the Netherlands, a waterway was filled during urban development which destroyed a flight path for *Myotis daubentonii* (pre-construction count: 27) (Koelman 2008). A temporary corridor was constructed to provide the bats with a temporal alternative route prior to construction of a mitigating bat tunnel. A before-and-after study assessed the use of a temporary corridor constructed with parallel fences made from plant protection fleece (H 1.7 m, L 204 m). The fence corridor was monitored in May 2008, after which it was adapted to shield the bats from light. It was monitored again in June 2008. As the corridor had to be moved to make room for the tunnel construction, a new tunnel was constructed parallel to and about 30 m from the original corridor. The new corridor was monitored in July 2008. Monitoring was done using bat detectors and visual observation.
On the first visit, 12 animals used the corridor, but for the most part they used the outside or flew above the corridor. After this visit, artificial street light was shielded off. On the second visit, 16 animals were using the corridor, flying between the fences. After this visit, the second corridor was constructed and the third monitoring visit showed that 15 animals were using it. It was concluded that the first corridor could be removed later in the year.

In an experimental before-and-after study, Britschigi et al. (2004) evaluated the effectiveness of new guiding structures (artificial as well as natural hedges) for a colony of *Rhinolophus hipposideros* in Switzerland.
The project took place from mid-July to mid-September 2003: 39 camera nights comprising 70 sessions suitable for analysis. Between the roost site building and the forest hunting grounds were large, open fields. The movements of the bats were studied and the individuals

counted by means of time-lapse cameras and infrared spots. One of the cameras was connected to a bat detector. The cameras were placed at the entrance of a chapel and at the experimental hedge area. The study was divided into non-overlapping phases 1) "Before", no hedges (one week), 2) Natural experimental hedges (five weeks), 3) Artificial experimental hedge structures enlarging the natural hedge (two weeks), 4) "After", no hedges (four days). The experimental hedge was a 180 m long, 1m wide and 1.5 - 2 m high guiding structure between the chapel and the forest. It was made from indigenous hedge plants. Later in the study, the first 90 m of the hedge was enlarged by camouflage netting to a width of 2 m and 2 m height.
Results showed that when emerging and returning, the bats flew towards the experimental hedges. During the seven weeks in which new hedges (natural and artificial) were available to the bats, the proportion of the "east-heading" bats using the hedges rose slowly, but continually and significantly, from 3% to 12%. The proportion of bats flying in each of the three main directions when emerging remained constant. Enlarging the experimental hedges with camouflage net did not have a significant effect on the number of bats flying adjacent to the structure. The experimental hedges constituted a shorter route to the foraging area than the original route for the "east-heading" bats. The bats using the experimental hedges spent up to 4 min. more at the foraging grounds than the bats using the original flight route. There were indications that the bats were willing to fly a detour adjacent to hedges instead of a shorter route with no hedges.

Fuhrmann & Kiefer (1996) conducted a 2-year experimental study in order to find methods to prevent road mortality of *Myotis myotis* as a new road was planned on the top of a former railway embankment directly in front of the old station building containing around 220 roosting female *Myotis myotis*. A construction was erected that could be modified to simulate an overpass as well as an underpass. In one of three trials, guiding walls leading to the structure were omitted. From the monitoring results, the authors concluded that the guiding walls seemed to be crucial to make the bats use the experimental construction.

Assessment and recommendations

We found eight studies investigating the use of screens, fences, mesh or vegetation as guiding structures or barriers. Five of those studies were designed to assess the effect of these measures, while the remaining two focused on other measures with screens being collateral.

Guiding fences or hedges were used by some of the monitored bats in two studies (Britschigi et al. 2004, Koelman 2008), and two additional studies found such guiding structures successful in guiding bats to a mitigation measure (Fuhrmann & Kiefer 1996, Picard 2014). In other studies, efforts to divert bats to new mitigation measures by planting trees and shrubs leading to the measure seemed unsuccessful (Berthinussen & Altringham 2012).
Lüttmann (2012 and 2013) found an increased movement of bats along fenced road stretches, particularly for *Myotis, Plecotus and Pipistrellus* species.
Studies also indicated that barrier screens erected at the road verges above culverts and river bridges increased the effectiveness of the underpasses and reduced road mortality at river crossings (Picard 2014).

Fences (5 m high) seemed to be effective in guiding some species safely across a railway (Flaquer et al. 2010), but more species-specific studies are needed to determine how and when such fences should be applied.

As we could find no studies assessing the effectiveness of hedgerows, treelines, screens and fences as guiding structures and barriers, such structures cannot be unreservedly recommended, but they have an obvious beneficial effect on many species. Hedgerows and trees may take years to mature to form an effective guidance structure. Species-specific before-and-after studies aiming specifically to determine the effects of hedgerows, treelines, screens and fences are needed to determine how effective such measures are.

3.5 Artificial roost sites

The construction of new roads sometimes involves the destruction of structures that are housing bat roosts. Most often it concerns the felling of old trees or demolishing buildings with bat roosts. Such destruction can pose a serious threat to the local population of a given bat species, especially if it concerns old and well established breeding or hibernation roosts, but perhaps less so if temporary roosts are involved.
A number of compensatory measures have been proposed. Basically, there are of two types of procedures: 1) establishing new artificial roosts near the old roost, e.g. installing bat boxes in trees or buildings or incorporating roosting structures in new buildings or in road structures such as bridges, and 2) moving tree trunks with existing roosts to a location very close to the original site or conserving large trees with a high potential for roosts near the transport infrastructure.

Understanding the sensory biology of bats is vital when artificially changing the position of bat roosts. Bats have an excellent homing ability and a number of migrating species have been shown to find their way back to a specific roost over hundreds of kilometres. Bats also have a very developed site memory and they rely on an eminent accuracy to imprint everything important in their local surroundings including the exact position of their roost (e.g. Dietz et al. 2009). However, bats primarily find their way by their highly specialized echolocation which only functions at shorter range. This means that although some bat species are actually very good at finding new roosting sites, it often takes them a long time (months or years) to do so. Some species like *Nyctalus noctula* have particular difficulties in finding new roost sites, but seem to be attracted to a roost by the social calls of conspecifics that are already in the roost, or they use eavesdropping by listening to echolocation calls of other species that use a roost (Gebhard 1997).

All this must be taken into consideration when decisions are made to establish new roosts for bats or to move existing ones.

3.5.1 Bat boxes and houses

Bat boxes have been recommended to compensate for the destruction of bat roosting or hibernation sites during development projects. Installing bat boxes on existing trees is a relatively easy and low-cost compensation measure that is widely used in several European countries (Marnell & Presetnik 2010, Korsten 2012, McAney & Hanniffy 2015).

In the following, we have included summaries of recent extensive reviews on bat boxes in order to briefly sum up the current knowledge level on bat boxes.

Summaries

Rueegger (2016) reviewed 109 publications originating from four regions; Europe (70%), North America (16%), Australia (12%) and Asia (3%). Publications reported box use for research (n = 67), conservation management (n = 42) and public bat awareness (n = 1). Woodcement as a box material was frequently used in Europe and was practically absent

elsewhere with timber boxes most commonly used overall. 20 species of bats have been recorded using boxes in Europe, although only nine were identified as using boxes commonly and 11 species were reported to have formed maternity roosts (*Barbastella barbastellus, Eptesicus nilsonii, Myotis bechsteinii, Myotis brandtii, Myotis dasycneme, Myotis daubentonii, Myotis nattereri, Nyctalus noctula, Pipistrellus pygmaeus, Pipistrellus nathusii,* and *Plecotus auritus*). The author found an overall lack of maternity and overwintering roost records in boxes.
Based on the findings in the 109 publications, the author presents some general recommendations and emphasizes that consideration should be given to the long-term maintenance costs of a box program. No conclusive evidence was found that box installation height is important for box use. There was a concern that boxes may provide a competitive advantage for bat species commonly using boxes. The author concludes that current bat box designs are poor substitutes for natural cavities, and that they should not be used as a justification for the removal of trees that comprise potential roost cavities.

A study monitored 390 bat boxes primarily installed as mitigation measures at road or rail projects (Christensen 2015). Clusters of five different boxes (four made of wood concrete, one of wood) were placed 4 m high in trees on seven study sites in Denmark. The boxes were monitored four times during two years.
Bat occupancy rate varied considerably between study sites. Three/four species were registered in the boxes during the first two years: *Pipistrellus pygmaeus/pipistrellus, Pipistrellus nathusii* and *Nyctalus noctula.* Bats did not seem to prefer any of the boxes more than others. No maternity roosts were detected. Bat boxes were often used by *Pipistrellus pygmaeus/pipistrellus*, but not where natural roosting sites were available. The boxes were rarely used if they were placed within 1 km of trafficked roads.

McAney & Hanniffy (2015) conducted a small, online survey in Ireland on bat boxes used as mitigation measures. They received contributions from eight sources, replying to specific questions and supplying general feedback.
Seven of eight respondents would recommend bat boxes as a suitable mitigation measure. Experiences with use of bat boxes involved almost only common species such as *Pipistrellus*. A general opinion was that bat boxes are useful as transitional and mating roosts, but only occasionally as breeding and hibernation sites. No data on occupancy rate or development of colony sizes were provided. The respondents were concerned that the lack of funding for post-erection monitoring affected the validity of proposing boxes.

Mering & Chambers (2014) conducted a meta-study on artificial roosts for bats by searching a large number of databases up to the year 2013. Unpublished data on the subject was also included. 47 publications provided data on the use of artificial roost structures. Most studies were from North America (19) or Europe (18). The publications comprised 48 types of structures used by 59 species. Roosts were constructed from wood (66.7%), concrete (8.3%), or other materials (25.0%) and varied in size and shape. Variables most often considered in the context of attracting bats were aspect, substrate, and mount location; few studies measured height or microclimate. Colonization rates ranged from 7% to 100%. There was no clear best choice for design and placement of artificial roosts; mimicking natural roosts seemed to be the most successful approach. In Europe, dominant species using the structures were *Plecotus auritus, Myotis daubentonii, Pipistrellus pipistrellus, Pipistrellus pygmaeus*, *Pipistrellus nathusii, Myotis nattereri,* and *Nyctalus noctula* and/or *leisleri*. Maternity colonies in the structures were registered for *Pipistrellus pygmaeus*, and *Pipistrellus nathusii*. The design of artificial roosts to support hibernating bats has largely been unexplored. The authors point out that as the artificial structures are most often used by common bat species, installation of bat boxes could increase interspecies competition and negatively impact rare species.

Korsten (2012) reviewed grey literature, conference proceedings and peer-reviewed papers on bat boxes and assessed their potential as a suitable mitigation and compensation method. The extensive review determines that many species use boxes as a mating roost, summer or winter roost, but maternity roosts in boxes are rare. Aggregations are generally smaller in boxes than in natural cavities. Factors determining bats' use of boxes are related to certain characteristics of the box (material, color, size, number of compartments, exposition to the sun, round or flat) and the place it is installed (height, exposition, free space around the box, amount of clustering of boxes). Using boxes for mitigation adds several constraints to a project, e.g. the time of overlap between the placement of the box and the destruction of the mitigated roost must be long. Therefore, Korsten (2012) recommend multitude of boxes for one lost roost. Choosing compensatory boxes that are suitable for the affected species and have the necessary functionality (maternity roost, mating quarters, over-wintering roost) is vital to the success of a bat box mitigation scheme.

Beck & Schelbert (1999) reported the first successful Swiss before-and-after experiments with migitating bat boxes for *Nyctalus noctula* and *Myotis myotis*.
Bat boxes were used on three occassions to mitigate the destruction of existing colony sites: 1) *Nyctalus noctula* colony in a roll-down shutter box on the face of an apartment building, 2) *Nyctalus noctula* colonies in roll-down shutter boxes as well as in facade cavities which they entered beneath the window sills, 3) *Nyctalus noctula* in bridge pillars which acted as a trap for the species. Box construction and placement was described in detail.
The bat boxes in all three cases were used by a large number of bats, and they also proved to be suitable for hibernation, with 100-300 *Nyctalus noctula* in each of the three boxes. The authors conclude that the following factors are of great importance for the success of the boxes: 1) Mitigating boxes must be placed immediately after destruction of the roosting site, 2) The boxes must be placed as close as possible to the original roost site. It did not seem to matter if the box was placed a few meter above or below the original site, 3) The entrance must resemble the entrance of the original roost. IR video showed that individuals search for similar crevices near the destroyed roosting site, 4) The mitigation box can be bigger than the original roost, but must not be smaller. Perennial temperature measurements from the described bat boxes, including a box made of only 1 cm thick wood, and from natural *N. noctula* hibernation roosts, including natural roosts in tree trunks, showed no significant differences. In all measured roosts, the temperature sank to well below 0 degrees C. The species seem to be adapted to such conditions. The authors doubt that the boxes can attract bats to locations where they are not already roosting.

Assessment and recommendations

We could only find one study aiming to determine if bat boxes installed as mitigation measures were actually effective in preserving local bat populations. The study which tested different bat boxes that were not installed to mitigate the loss of a particular roost but rather as a general habitat improvement measure, showed that boxes were only used by common species, and only as mating quarters (Christensen 2015).

Numerous studies of bat box schemes that were not related to roads or railways, have tested various bat box designs (e.g. Beck & Schelbert 1999, Dietz et al. 2009, Korsten 2012, Rueegger 2016). The general conclusion in all the reviews of bat boxes is that they cannot serve as a replacement for natural roosts. A general tendency of great concern is the overall lack of maternity roosts and particularly overwintering roost records (Korsten 2012, Mering & Chambers 2014, Rueegger 2016). Several authors raise a concern that bat boxes may provide a competitive advantage to some species, primarily more common species such as *Pipistrellus* sp., which are often registered in bat boxes (Mering & Chambers 2014, Rueegger

2016). Despite the fact that some local bat box projects successfully manage to attract maternity roosts of certain bat species, e.g. *Pipistrellus pygmaeus, Myotis bechsteinii, Myotis nattereri, Nyctalus noctula* (J. van der Kooij and M. Göttsche, pers. comm.), an effective bat box scheme widely applicable to each bat species throughout their European range is not imminent.

A study which evaluated three cases where bat boxes were custom built to replace known roosting structures, successfully managed to maintain roosting and even overwintering bat (*Nyctalus noctula*) colonies (Beck & Schelbert 1999). According to the authors, a prerequisite for the success of these boxes were the fact that they were placed where bats were already roosting. Consequently, similar successful results may be difficult to obtain in most road projects, as bat roosting sites in trees or houses normally have to be completely removed, and compensation roosts established at other locations. However, designing such custom-made bat boxes could be relevant in cases where existing road structures such as bridge abutments are being altered or renovated.

Based on the reviewed information, we cannot recommend bat boxes as a compensatory measure for roosting sites that are destroyed by road construction projects. Bat boxes might be used as a short-term supplementary measure, offering bats temporary roosting sites (Christensen 2015, Dietz et al. 2009). However, such temporary roosting sites may be of little value to bats as long as no effective measure compensating for the roost loss itself can presently be advised. Therefore great care should be taken to preserve bat roosts and avoid removal of known and potential bat roosting structures.

More studies evaluating each bat species' use of bat boxes are needed, including studies aimed specifically at evaluating bat boxes that are installed as compensatory measures in road construction projects. With the current knowledge on bat boxes, post monitoring should always be conducted if bat boxes are used as a mitigation measure in order to determine if they have fulfilled their purpose. Road agencies should be aware that bat boxes need to be installed well in advance – preferably several years – of removal of existing potential roosting sites. Experiences show that although bat boxes may be occupied quickly, it takes several years before boxes are regularly occupied and potentially used for breeding (McAney & Hanniffy 2015).
Results indicate that placing bat boxes too close to the new road may affect their occupancy negatively (Christensen 2015, McAney & Hanniffy 2015). The vast majority of bat box models need regular inspection in order to remove bird or wasp nests, to clean the boxes from bat faeces (unless "self-cleaning" box designs are used), and to ensure that the boxes are still in place. Furthermore, wooden bat boxes need to be replaced with 3 year intervals (Beck & Schelbert 1999).

3.5.2 Bridges as roosting structures

Roosting bats have been recorded in bridges in many European countries (e.g. Smiddy 1991, Billington & Norman 1997, Sunier & Magnin 1997, Beck & Schelbert 1999, Richarz 2000, Pysarczuk 2004, Celuch & Ševčík 2008, Pysarczuk & Reiter 2008, Amorim et al. 2013, Ouvrard 2013, Gottfried & Gottfried 2014, Harrje 2015, Wojtaszyn et al. 2015). Cavities, gaps and crevices in both old and modern bridges may resemble the conditions occurring in natural roosts for many bat species. The bridge can serve as a roosting site for bats throughout the year or parts of the year and may be used as breeding, hibernation and transition roost quarters. Although bridges can occasionally reach adequately high temperatures for breeding, they are most often used as transition roosts or hibernation quarters (Richarz 2000).

Bridges have been (retro) fitted with mitigation structures to accommodate bats in some European countries (Sunier & Magnin 1997, Beck & Schelbert 1999, Billington & Norman 1997, Heijligers 2005, Ouvrard 2013).

Summaries

The 120-year old Levensau bridge spans the Nord-Ostsee Canal in Kiel-Suchsdorf, Germany. The 2-3 cm wide and more than one meter deep expansion joints in the bridge's brick abutment are used by hibernating bats (Harrje 2015. They enter the abutment pillar cavity through a large arched window 16 m from the ground. In the 1990s, it was the largest Central-European winter quarter for *Nyctalus noctula* with around 5,000 individuals. Six other species hibernate in the abutment: *Pipistrellus pipistrellus, Pipistrellus pygmaeus, Myotis nattereri, Myotis daubentonii, Myotis dasycneme* and *Eptesicus serotinus.* A monitoring programme which commenced in 2008 showed that by 2015 the noctule population had declined to around 1,000 individuals, while the pipistrelle population had increased.
The canal and the bridge construction are to be widened to accommodate the larger ships. The project requires the northern abutment pillar to be demolished while the southern pillar will be left for the bats. In order to relocate the bats from the northern to the southern pillar, the entrance window has been blocked from time to time in order to "train" the bats to use the southern pillar. In 2014/15 the relocation effort resulted in 5,000 of the 6,000 hibernating bats using the southern pillar. An increase in hibernating *Pipistrellus pipistrellus, Myotis nattereri and Myotis daubentonii* in the southern pillar documented the successful relocation of these species. The noctules have not yet accepted the relocation and still hibernate in the northern pillar.

Heijligers (2005) visited artificial hibernacula roosts in bridges that were built as part of a new motorway (A73) in The Netherlands as compensation for destroyed roosts. The two artificial hibernacula were built as cellars into the earth body of the bridges or the earthwork leading up to the bridges. Bat boxes were placed inside the two cellars. The cellars and the boxes were checked year round in 2003-2005. None of the boxes in the hibernacula were used, but the authors found 3 and 5 *Pipistrellus pipistrellus* in the two cellars, respecitvely.

The Swiss A1 motorway crosses the river Reuss on a 60 m high viaduct supported by six pillars which are used by a small number of *Myotis myotis* for roosting during the summer (Beck & Schelbert 1999). The bats enter the relatively narrow space inside the pillars through a vent in the upper part of each pillar, and rest on rough patches of concrete inside. However, in contrast to *Myotis myotis,* the pillars acted as a trap for *Nyctalus noctula* because this species cannot manoeuvre in the narrow space inside them. They ended up on the very bottom of the pillar and could not climb the smooth concrete surface back up to the entrance vent. The problem was solved by inserting wooden bat boxes inside each of the six pillars right behind the vent, preventing the bats from entering the pillar cavity. Bat boxes were made from 5 cm thick massive spruce. Only two months later, all boxes were used by *Myotis myotis*; by resting males during summer, and for mating in autumn. In winter *Myotis myotis* were still absent. Six months after the boxes had been installed, 25 *Nycalus noctula* used one of the boxes successfully for hibernation. The following two winters, the same box was used by 2-300 hibernating *Nyctalus noctula*. The next winter, even more individuals had apparently attempted to hibernate in the box, and the animals had either suffocated or squeezed each other to death in the tight box. Therefore the box was enlarged and the massive floor of the box replaced with a plastic coated metal mesh. Aside from providing ventilation to the box, this solution had the advantage that bat droppings and urine could pass straight through it. Furthermore, boxes could be checked without opening them. The authors also recommend the entrance hole be placed at the bottom of the box, instead of at the top as they did in the first box design.

In 1987 the Corbières Bridge in Switzerland needed to be renovated (Sunier & Magnin 1997). During inspections prior to the renovation, a maternity colony with 180 female *Myotis myotis* bats was found in the interior of the bridge. This was one of the largest colonies of the species in Switzerland. In order to maintain the bridge as a roosting site for *Myotis myotis,* mitigation measures were incorporated into the renovation project. Renovation work was restricted to the winter season when the bats were in hibernation elsewhere and easy access points for the bats were maintained. To maintain favourable conditions for the roosting bats rough materials were used for the interior surfaces of the chamber and rain water was channelled into the roosting chambers to maintain a high humidity and temperature. Provisional work to install heating was also incorporated. Temperature and humidity in the roosting chambers were monitored for 4 years (1991-1994) and no significant changes were observed. The size of the maternity colony initially dropped to 150 females and the juvenile mortality increased from 4% to 35% in 1991, but by 1994 the colony size has increased to 200 females.

In “The Conservation of Bats in Bridges Project”, 2,555 bridges were surveyed in Cumbria, UK (Billington & Norman 1997). 320 (12.5%) were confirmed as bat roosts, and 1039 (41%) had suitable crevices but no proven roost. *Myotis daubentonii* was the most frequently identified species, and was found in 92 bridges (3.6%). *Myotis nattereri* was recorded in 25 (1%) bridges. Other species recorded in small numbers were *Pipistrellus pipistrellus, Plecotus auritus, and Myotis mystacinus/brandtii.* Most roosts (75%) were located in bridge spans but bats were found to roost in a wide variety of crevices in a range of bridge structures. The main requirement for a potential roost site is that the crevice should be at least 10 cm deep and protected from the elements. Roosts were more frequently recorded in bridges over watercourses than other bridge types, and bridges with roosts showed a strong association with slow-flowing water and broad-leaved trees. Bats showed little selection for altitude or arch height. Bridges with concrete spans were less likely to contain roosts than stone span structures, which corresponded to the relative scarcity of suitable crevices in concrete spanned bridges. Bridges carrying active railway lines had a very low occupation rate (2%), whilst bridges carrying farm tracks had a high occupation rate (25%). UK bridge projects where measures for bats have been incorporated include insertion of bat roosting crevices or larger bat boxes into the bridge abutment or bridge arch. We have not found any studies documenting whether these measures were actually successful.

An incident of mass mortality of bats in a transient aggregation of *Nyctalus noctula* in a motorway bridge near Mannheim, Germany, was investigated and described (Häussler et al. 1997). In 1995, the bats were removed from the site regularly and examined (sex, age, forearm, weight, reproductive condition). Observations on bat behaviour were also made. All samples consisted almost exclusively of post-juvenile bats, with females prevailing. The young noctules suffered from severe undernourishment, accompanied by opportunistic bacterial infections and possibly effects from chlorinated hydrocarbon residues. From observations on the bats' behaviour, evidence has been obtained that most of them did not emerge from the bridge to forage but got trapped in the tunnel-like steel construction spanning the river as they could not make use of the exits. This was likely due to the flight and echolocation characteristics of that species, complicated social factors, and the high number of bats present at the bridge roost. Successful architectural alterations were made, preventing the bats from passing into the inner steel construction but allowing them to roost in safe parts of the bridge.

Bridges as roosting structures in the USA

Several large studies of bats in bridges have been conducted in the USA. Although the bat species in the studies are not present in Europe, the information on substrate type, crevice width, construction design etc. preferred by the bats may translate to European conditions and inspire the design of future bridge constructions in Europe.

A replicated survey of 130 highway structures (125 bridges, five culverts) in three Montana counties (USA) determined the presence of roosting bats (Hendricks et al. 2005). General bridge surveys were conducted during daylight hours in 2003. In 2004, the occupancy of the day roost structures that were identified in 2003 was monitored. When bats were discovered at a structure, the following information was noted: species, estimated number of adults present, evidence (pups) that the roost was a maternity colony, and measured or estimated roost height. The information was statistically analysed. Furthermore, landscapes around each highway structure were analysed at radii of 0.5 km and 3.0 km to look for possible relationships between adjacent land cover types and structure use by bats.

There was evidence of bat use at 78 structures (60.0%); 66 structures (65 bridges, one culvert) apparently were used exclusively for night roosting (nocturnal rest sites for digesting meals in a protected location), and 12 bridges were day roosts (sites protected from weather and predators for raising young and/or sleeping during the day). Four species of bats were identified in 2003 using highway structures for day roosting: *Eptesicus fuscus, Lasiurus cinereus, Myotis lucifugus,* and *Myotis ciliolabrum*. The use of bridges by bats was generally unrelated to the surrounding landscape at two buffer scales: 0.5 km and 3.0 km. Bats used 75.9% of concrete structures, 37.5% of steel structures, and 31.6% of wooden structures. Significantly more T-beam and box-beam concrete structures were used than slab ones. Night roosts were found in a wider variety of bridges than day roosts, and included one steel culvert.

Feldhamer and co-workers (2003) conducted a survey of 232 bridges in 9 southern Illinois counties (USA) for the presence of roosting bats. From May through July 2001, and June through August 2002, 232 bridges were surveyed for the presence of roosting bats. Of the 15 bridges with bats, 11 were later resurveyed to determine continuity of use. The bridges were generally ≥ 20 m long. Five bridge designs were identified:

- Parallel box beam bridges were concrete with crevices (expansion joints) the length of the bridge. The crevices varied in width up to about 5 cm, they were about 46 cm deep, and protected from above against moisture.
- Prestressed girder bridges were concrete with inverted T-shaped girders occasionally with steel bracing.
- Cast-in-place bridges had various patterns and sizes but were generally concrete “waffle-shaped” structures.
- I-beam bridges had steel girders in association with concrete or wood.
- Flat slab bridges were usually concrete box culverts with no crevices or girders.

Fifteen bridges (6.5%) had bats roosting at the time they were surveyed. The species registered roosting were *Eptesicus fuscus, Pipestrellus subflavus, Myotis lucifugus* and *Myotis septentrionalis*. The number of bats per bridge ranged from 1 to >100. Bats occurred in four of the five types of bridge designs surveyed; flat slab bridges were never occupied by bats. Of the 15 bridges with bats, 11 were rechecked and seven of these (63.6%) were being used by bats when rechecked. From this, the authors derived an estimated usage rate of about 10% of the 232 bridges surveyed. The average elevation of 9 roosts was 5.1 m (range 1.0 to 10.0 m) above ground level under bridges. One individual roosted on a steel girder; all others roosted on concrete surfaces. No bats roosted on wooden surfaces. The greatest concentrations of bats were in the crevices of parallel box beam bridges. Minimum crevice width of parallel box beam bridges used by bats was approximately 1.9 cm; most bats were in crevices ≥ 2.5 cm wide.

Bridges and culverts were evaluated as bat roosting habitat in 25 U.S. states at elevations from sea level to 10,000 feet (Keeley & Tuttle 1999). Advice for incorporating bat roosts, both before and after construction, was provided. Environmental and economic benefits, impacts on structural integrity and public safety, and management of occupied structures were discussed.
Field studies, literature reviews, and interviews with biologists and engineers were conducted to determine which bat species use North American highway structures, to identify their roosting preferences, and to develop methods of predicting where bats will use them. 2,421 structures (1,312 bridges and 1,109 culverts) were surveyed for bat use. Sixty different characteristics were used to determine bat roosting preferences.
Approximately 4,250,000 bats of 24 species were discovered living in 211 highway structures. Only one percent of existing structures had ideal conditions for day roosting, but at little or no extra cost a much larger percentage could provide roosting opportunities for bats in the future. Most species chose concrete crevices that were sealed at the top, at least 15-30 cm deep, 1.3-3.2 cm wide, and 3 m or more above ground, typically not located over busy roads. Bats used parallel box beam bridges as day roosts more than any other kind. The second most preferred bridges were cast in place or made of prestressed concrete girder spans. Metal and small concrete culverts were the most frequently encountered highway structures and were the least preferred as roosts. The authors found substantial regional variation in the frequency with which bats used suitable highway structures as either day or night roosts. Retrofitting existing bridges and culverts proved highly successful in attracting bats, especially where bats were already using them at night. Advice for incorporating bat roosts, both before and after construction, is described in detail in a manual which can be downloaded on the homepage of Bat Conservation International: http://www.batcon.org/pdfs/BatsinBridgesManual.pdf

Assessment and recommendations

We found evidence that it is possible to maintain or even improve conditions for *Myotis myotis* and *Nyctalus noctula* in bridges when they undergo renovation work or are being modified to accommodate bats. Evidence includes a case of hibernating and breeding, as well as more transient bat aggregations: Bat boxes inserted into the Reuss Bridge's pillars maintained and apparently increased the use by *Myotis myotis* (summer roosts, but not maternity colonies) and *Nyctalus noctula* (hibernating) already roosting in the bridge (Beck & Schelbert 1999). Incorporating a roosting chamber with rough walls and water passing through it, the arches of Corbières Bridge during renovation sustained and possibly helped to increase the number of individuals in a *Myotis myotis* maternity roost (Sunier & Magnin 1997). At the Levensau high Bridge, individuals of *Pipistrellus pipistrellus, Myotis nattereri and Myotis daubentonii* were successfully relocated from the bridge's northern abutment to the southern, both of which were previously used as a hibernation roosts for the species. Relocation has not yet been successful for *Nyctalus noctula* (Harrje 2015).

One of the key factors in ensuring that bats will use an altered or new replacement roost seems to be related to keeping the shape and position of the entrance to the roost as close the previous roost as much as possible. Infrared recordings of *Nyctalus noctula* show that after the removal of their roosting site on a building, the bats search for identical entrance openings (Beck & Schelbert 1999). As seems to be the case with new roosting sites in general, it is important that the new roosting site is available immediately after the disturbance of the old site as possible.

We found some cases where bat roosting opportunities had been built into new bridge constructions in The Netherlands as well and in the UK (Billington & Norman 1997, Heijligers 2005, http://www.dearchitect.nl/projecten/2015/detail/vlotwateringbrug/vlotwateringbrug.html), but only one short-term study of the efficiency, showing that only the outer chamber of an artificial hibernacula in the earthwork of a bridge was used by a couple of *Pipistrellus pipistrellus.*

The American studies all show that parallel box beam bridges are most likely to provide crevices that are suitable for roosting bats without being modified (Feldhamer et al. 2003, Hendricks et al. 2005, Keeley & Tuttle 1999). In the UK, stone bridges contained more roosts than concrete bridges (Billington & Norman 1997), but stone is rarely used in the construction of new bridges. Furthermore, roosts were more frequently recorded in bridges over watercourses than in other UK bridge types.These factors could be considered if attempting to create potential bat roosting sites in bridges.

Based on the reviewed literature, we find that the addition or modification of bat roosts in bridges is a promising mitigation measure where bats are already present. A couple of cases showed such mitigation measures where *Nyctalus noctula* and *Myotis myotis* was present, but studies are needed to determine how effectively such measures can be applied to other species. As roost design seems to be highly dependent on existing conditions, no specific procedure is likely to work in every case. New or modified roosts need to be continually assessed and adjusted if necessary over several years as experience shows that small design flaws can cause high bat mortality.

One of the obstacles posed by artificial roosting sites in general is that bats are often slow to detect them, particularly if they are not close to the original roost. For this reason they do not effectively mitigate for the destruction of bat roosts. Further studies are needed to show if and how bats can be attracted to new roosts in bridges, and whether they can be part of a long-term mitigation strategy. The potential mortality risk for the roosting bats when emerging from or arriving to the roost due to the proximity of traffic should be considered when assessing the effectiveness of artificial roost sites in bridges.

3.5.3 Artificial holes in existing trees

Suitable natural roosting cavities in trees develop very slowly. Cutting slits, drilling holes or enlarging natural hollows in living trees may help to create suitable roost cavities quicker than the natural decay of trees. If the procedure is effective, it could be used to facilitate the development of bat roosts in nearby preserved forest areas.

Summaries

A small-scale project (Andersen et al. 2014) was launched in 2014 in a Danish forest with a high bat species diversity comprising 11 species. The forest owner wished to improve and consolidate the species richness in the forest. The conservation actions included cutting deep slits were made in old beech trees (*Fagus sylvatica*). Furthermore, a small number of hollows in old oak trees were enlarged in such a way that they resembled suitable bat roosts. The trees are continually monitored, and bat behaviour at the trees is studied. The 2015 monitoring found no bats using the slits or hollows (H.J. Baagøe, unpubl.).

In 2009, a *Nyctalus noctula* maternity roost with up to 75 lactating females was recorded in an ash tree (*Fraxinus excelsior*) in a semi-natural woodland in the United Kingdom (Damant & Dickins 2013). The ash tree was accidentally felled in December 2011 as the tree was considered to be a public safety concern. A 3.4 m long section of the tree trunk including the bat roost site was quickly reinstated on a nearby tree. Furthermore, cavities were created in nearby trees to stimulate rot, and five bat boxes were installed.
Post mitigation surveys in 2012 and 2013 have confirmed that the *Nyctalus noctula* roost in the relocated tree trunk was used during the maternity periods. The number of roosting bats was consistent with in the number of bats using the roost prior to the felling. The bat boxes were only used by nesting birds. No results have been reported on the artificial tree cavities. Presumably, they have not developed to be sufficiently large to house a bat roost.

Assessment and recommendations

We did not find any evidence that bats roost in artificial holes or crevices made in living trees. We encourage further studies aimed at determining their use by bats over several years, different species preferences to cavity size and shape, and optimal carving/drilling procedures. Because we only partly understand all the parametres determining a good (maternity) roost for each individual bat species, it is important to experiment with a range of different solutions.

3.5.4 Translocation of tree trunks

Translocation of tree trunks with bat roosts has been suggested as a very last resort if the tree cannot be saved (Limpens et al. 2005, Damant & Dickins 2013). The tree is very carefully felled, and the section containing the cavity is strapped on to a nearby tree trunk. If bats are present in the roost at the time of the translocation, the exit hole(s) are temporarily blocked and the trunk is kept vertical throughout the procedure. Alternatively, the whole trunk is translocated, and the base of it dug into the ground, but this method is likely to shorten the "lifetime" of the trunk considerably.

Summaries

In 2009, a *Nyctalus noctula* maternity roost with up to 75 lactating females was recorded in an ash tree in a semi-natural woodland in Buckinghamshire, United Kingdom (Damant & Dickins 2013). The ash tree was accidentally felled in December 2011 as the tree was considered to be a public safety concern. A 3.4 m long section of the tree trunk including the bat roost site was quickly reinstated on a nearby tree. The tree trunk was orientated to recreate the orientation and height of the access holes for the bat roost prior to felling. Furthermore, cavities were created in nearby trees to stimulate rot, and five bat boxes were installed. Post mitigation surveys in 2012 and 2013 have confirmed that the number of *Nyctalus noctula* using the roost in the relocated tree trunk in the maternity periods was consistent with the number of bats using the roost prior to the felling. The bat boxes were only used by nesting birds.

A churchyard avenue of 114 Lombardy poplars (*Populus nigra 'italica'*) in Denmark has been hosting breeding colonies of *Nyctalus noctula* through many years (Baagøe 2015 unpubl.). By 2014, the 80-year-old poplars constituted a risk for the public, and the poplars had to be felled. 12 trees with hollows that either had bat roosts inside or showed signs of use by bats were protected. Five 1.5 m long trunk pieces were split and a "lumen" was created in each half to simulate a well-insulated *Nyctalus noctula* roost. The halves were reassembled and mounted on large trees near the original roost sites. Of the remaining 12 "bat trees", five were allowed to remain unfelled for a few years, but as "torsoes" with the hollow trunk parts

with bat roosts intact. The other seven trees were carefully taken down in pieces keeping each hollow piece (bat roost) as one entire entity. These hollow bat trunks (8 in total) were immediately mounted in nearby trees. During the process sounds from within one of the trunks, likely from semi-lethargic *Nyctalus noctula*, were heard.
The translocated tree trunks were monitored from May - November 2015. In this period, experiments were set up to help the bats find the new roost positions by playing back recorded noctule calls and calls of swarming bats from a bat lure mounted next to some of the mounted “bat roost trunks”. Preliminary results show: 1) *Nyctalus noctula* continued to hunt and commute in the area, 2) Single or a few bats continued to use the roosts in the “torsoes”. In late summer and autumn they were observed departing and arriving from these roosts; upon return single individuals sitting in the hollows started emitting the deep calls characteristic of the male advertising song, 3) From early August and onwards a varying number (up to 21 individuals) were using the only trunk that we translocated with bats inside. This may indicate that they had learned the new location of the trunks when leaving them the previous autumn. 4) So far none of the other trunks seemed to have been used as roosts by bats, but *Nyctalus noctula* was successfully attracted to them by the sounds from the bat lure. However they could not be observed landing on the trunk or entering.
The results are moderately promising and the monitoring and experiments continue in 2016. The experiment cannot be considered a success until the bats have been shown to breed in the roosts as before the avenue trees were felled.

During construction ofa motorway in Silkeborg, Denmark, a colony of *Nyctalus noctula* which had been overlooked in the environmental impact assessment was discovered in a small forest area shortly before it was due to be felled. Although the colony birch tree (*Betula pubescens*) was rotten and fragile, it was decided to move the crownless tree, and very carefully and strap it onto a nearby tree. Four other trees trunks with natural cavities were relocated as well.
The *Nyctalus noctula* colony tree was relocated but the top of the trunk broke off during the process. This did not damage the bats, but as the roost now had an opening at the top, the bats disappeared shortly after the relocation. The location was visited in the summer after the relocation and in October 2016, but there were no bats in any of the tree trunks (J D Møller, unpubl.).

Assessment and recommendations

We found evidence from only one study (Damant & Dickins 2013), which shows that it is possible to successfully relocate tree trunks with bat roosts (*Nyctalus noctula*). The method needs much more research and testing. It is plausible that moving the tree trunks with the bats inside may be the best solution as it gives the bats an opportunity to imprint the new position of the roost trunk.

Translocating tree trunks is a highly invasive measure and it should only be used in cases where there is absolutely no possibility of preserving the roost tree. Whenever it is done, we strongly recommend that the translocated tree trunks are monitored. Using played-back bat calls to lure the bats to the relocated roosts might be helpful, particularly for species such as *Nyctalus noctula*, which use eavesdropping when locating new potential roost sites (Gebhard 1997). The measure has a restricted lifetime, as the relocation tree trunks may decompose relative quickly,

3.5.5 Tree retention

Structural diversity of forest is positively correlated with bat activity (Froidevaux et al. 2016), but in many production forests the occurrence of mature and decaying trees is low and declining. This shortage of suitable tree cavities for roosting sites might be a limiting factor for bats. A wide range of age groups of trees, which can develop into suitable roosting trees, should be available to maintain the long-term habitat quality of forest. Protection of single trees or diverse forest stands has been suggested as ecological mitigation for bats in development projects to improve the long-term availability of roosting trees and off-set the impact of roost site destruction on population scale.

Tree retention has been applied to compensate for the destruction of large potential roost trees on a railway improvement scheme in Denmark (Ringsted-Fehmarn) (M. Ujvári, pers. comm.). 125 individual trees in eight forests along the 110 km long railway has been preserved and left to natural decay. The trees were registered as protected by restrictive covenants on the property and the landowners were granted economic compensation.

No studies have been conducted to evaluate tree retention as a conservation tool and a compensatory measure for development projects. The scale of the benefits and the time taken before the intervention becomes effective is unknown, but the method is obviously beneficial as a long-term conservation measure for bats. Depending on the potential for cavities in the protected trees, short-term measures may also be needed as a supplement to prevent losses of bat colonies.

3.6 Habitat improvement

Habitat improvement is sometimes suggested as a compensatory measure for the loss of feeding areas or general habitat loss and degradation in relation to construction of roads (Limpens et al. 2005). It can consist of measures such as improving the quality of existing habitats or (re)creation of lakes, ponds or wetlands, afforestation, and extensification of grazing and land use.

Summaries

A road in Wales, UK, was widened from two lanes to four lanes. The road project was within 300 m of a *Rhinolophus hipposideros* maternity colony, and habitat improvement was chosen as one of the mitigation measures (Wyatt 2010, Pickard 2014). A 2.2 ha *Rhinolophus hipposideros* feeding habitat was created from a grazed field by slowing down of stream, excavation of shallow pond, managing the grass area to be become more bat friendly (eg. allowing flowering plants to flower before cutting) and plantin insect friendly shrubs and trees. The habitat improvement was completed in 2008, and annual monitoring has so far shown slow uptake in the use of the area for feeding (1 or 2 individuals per year from none at all).

Assessment and recommendations

We found no studies assessing the effect on bat populations of habitat improvements made specifically for bats. A Welsh case study showed limited success so far. Two studies have evaluated bats' use of artificial ponds. In an American replicated, controlled, site comparison study, artificial ponds in a managed pine landscape were used significantly more than adjacent natural wetlands (Vindigni et al. 2009). Total bat activity was found to be significantly higher above retention ponds than above the surrounding vineyards in a German replicated study (Stahlschmidt et al. 2012). These studies show that artificial ponds can be attractive feeding areas for bats, but not if they increased carrying capacity for bats in the area.

Intuitively, we would expect that habitat improvements would increase the area's carrying capacity for bats, which may balance the detrimental effects of the roads. However, there is a general lack of studies evaluating the effects of habitat improvements implemented for bats. Creating artificial ponds seems to be an efficient way to increase feeding areas for certain bat species (particularly *Myotis* and *Pipistrellus* species). It is important to keep in mind that the retention basins which are placed close to new motorways may also increase the bats' risk of vehicle collisions. Studies of the effects of placing such basins close to motorways should be conducted.

The effect of other types of habitat improvement on bat populations seems largely unexplored. Berthinussen & Altringham (2012) recommend foraging habitat improvement within 1 km of roads in order to reduce the barrier effect. We recommend long-term studies assessing which habitat factors are vital to maintain bat populations.

4 Conclusions and perspectives

Roads may affect bats directly through increased mortality, light and noise disturbance, habitat loss and degradation, and indirectly by fragmenting populations and their habitats. The life history of bats and landscape use make them highly vulnerable to increased mortality rates, reduced reproductive output and landscape modifications e.g. due to changes in human land use and road developments.

All bat species are of conservation concern in Europe. The most effective conservation strategy to minimise the impact of a new road would be to avoid areas that are most important for bats i.e. areas with a high diversity of species, host populations of especially rare species, valuable foraging areas or commuting routes. Should it not be possible to avoid such areas, the road construction must include measures to mitigate or compensate for the detrimental effects of the road to maintain favourable population status of the affected bat populations.

Based on an extensive knowledge of bat ecology and behaviour, bat researchers, consultants and road developers have designed various mitigation methods with the intention of reducing mortality, increasing road permeability, to compensate for habitat loss and degradation, and thus avoid declines in local populations. These mitigation methods have been implemented on numerous locations in Europe and elsewhere over the last decades. Although these measures could work in theory and bats in many cases have been observed crossing roads as intended using the measures, the measures have rarely been monitored adequately in the field to evaluate their effectiveness.

Bats have a complex biology and their habitat use, flight and echolocation behaviour varies significantly between species. On one hand bats are often very conservative in their behaviour and show high fidelity to roosting sites, commuting routes and hunting areas, but on the other hand they sometimes very quickly adapt to changes in the landscape. Bats will often react unexpectedly to drastic and sudden manipulations in the landscape such as road constructions. This means that without proper testing of the effectiveness of each mitigation method, including every minor simplification or refinement, there is no guarantee that the measures may actually have the intended effect and maintain a favourable status of the bat populations near the roads.

The present review was carried out to clarify the extent to which the various mitigation measures have been tested and to evaluate the quality and quantity of evidence for their effectiveness. The studies on each type of mitigation measure for bats were reviewed to evaluate if the measure could be characterised and recommended as an effective method, or whether it showed potential for further improvements or refinements that could increase its effectiveness to an acceptable level.

To compile the most up-to-date and comprehensive information on mitigation and compensating measures for bats on road infrastructures, we received information from road authorities, bat researchers and other stakeholders in all European countries. We not only looked for scientific papers published in peer-reviewed journals, but also made a great effort to find all kinds of “grey literature” and reports in local languages. Nevertheless, we have almost certainly missed some publications. We are aware that some studies may not have been published at all. Other studies are the property of the road developer and were not publically available. We cannot guarantee that we have found every evaluation of bat mitigation measures, but stakeholders throughout Europe have had the opportunity to contribute with evidence.

We identified less than 50 studies on bat mitigation methods on roads and railways. The studies varied widely in design and quality taking into account how many parameters that may influence the effectiveness in each individual case. Many studies examined more than one type of intervention but most often only included few replicates of each type. Most of the surveys only aimed to record bats' use of the measures, as opposed the effectiveness. The present review suggests that studies with a proper robust scientific approach to evaluate effectiveness have only been published in very few cases. Only two long-term studies that included monitoring of the population development have been reported. This is a critically low number of studies considering the numerous mitigation measures that have been installed at European roads and railways, and the costs associated with these interventions.

Because of this deficiency of adequate testing and research, very little can be concluded about the effectiveness of the different mitigation methods. In the worst-case scenario some interventions could actually have the opposite effect by adding to the risk of bat-vehicle casualties. The present, insufficient knowledge makes it difficult to thoroughly evaluate most of the mitigation methods, and to suggest improvements or corrections that could make them sufficiently effective to be recommended. As a consequence of the limited evidence of the effectiveness of the mitigation and compensation measures, and the ill-defined goals for the constructed measures, road authorities may continue to invest resources on untested and possibly ineffective measures.

Tentative assessment of effectiveness of measures

Based on the evidence of bats' use of the mitigation and compensation measures and their effectiveness in the reviewed literature, we have tentatively assessed the measures potential to mitigate road effects on bat populations. The measures were categorised as:

1/ A recommendable intervention if located and constructed correctly. Good evidence that bats use the structure or that the method is effective.
2/ A potential effective intervention which shows encouraging results. Further assessment awaits better documentation of effectiveness or development of the measure.
3/ An intervention where more research is needed to assess its potential. Studies indicate some use by some species.
4/ An intervention proved to be ineffective, studies have shown very ambiguous results, or it cannot be used as a compensation method. Not recommendable.

Measure		**Assess-ment**	**Comments**
Overpasses			
Bat gantries	Open structures	4	Wire gantries have been shown to be ineffective. No need for further research. Other open-structured designs (mesh and lattice structures) are probably ineffective as well.
	Closed structures	3	The effectiveness of gantries resembling small bridges has not been adequately tested. Such research is required to assess the potential of these types of bat gantries.

Mitigation method		**Assess-ment**	**Comments**
Hop-overs		3	Many descriptive studies but few robust evaluations of hop-overs. A potentially effective measure for some species but ineffective for others. Surveys determining the best placement are a key in successful use. Not recommendable before better documentation on species-specific effectiveness is available.
Wildlife overpasses		1	Use by a range of functionally diverse bat species well documented. Recommendable measure if constructed optimally and with high connectivity to adjacent bat habitats.
Modified overbridges	Green verges	1	Little documentation of effectiveness, but a promising measure if the vegetation is well-connected to existing commuting routes. Recommended measure as a supplement to passages dedicated to bats.
	Panels	3	Successful experiments have been reported for some bat species. General effectiveness is not documented. Awaiting further development and testing before a conclusive assessment is possible.
Other technical over-road structures		4	Reports of low or incidental use of road overbridges and road sign gantries if structures are located at existing commuting routes. Cannot be recommended as suitable crossing sites for bats. Overbridges should be modified if located on commuting routes.
<u>Underpasses</u>			
Tunnels and Culverts		2	Good evidence of effectiveness for low-flying manoeuvrable species, if located on an existing commuting route. Recommendable for this functional group of species if dimensions are sufficiently large. Species-specific size requirements should be more thoroughly investigated.
Viaducts and river bridges		1	An obvious, potentially effective measure for a wide range of functionally diverse bat species. Recommended structure where roads intersect valleys and lowlands because habitat and landscape features under the bridge are preserved.
<u>Other interventions</u>			
Hedgerows and treelines		2	Ambiguous evidence that guiding structures effectively encourage bats to make major detours from established commuting routes. New hedgerows and treelines will take years to develop into effective guiding structures. Recommended as part of a long-term mitigation strategy if combined with safe crossing structures.

Mitigation type		**Assess-ment**	**Comments**
Barrier screens		2	Studies indicate that fewer bats cross road sections with barriers, and that screens lower mortality rates at roads near underpasses. Potentially a recommendable method when accurately constructed and if combined with safe crossing structures.
Artificial lighting	Deterrence of bats	3	Indications of successful deterrence of some species, but only a few studies have attempted to evaluate the method. Further research needed to assess the potential effectiveness of the measure.
	Adaptation of light spectrum	3	Adaptation of streetlights to reduce aggregations of insects and foraging bats over roads. No studies on the potential effectiveness available. Needs further species-specific research to assess the effectiveness of the measure.
	Restriction of light spill	2	Restricting streetlights to reduce general light pollution in order to enhance use of multifunctional passages. Positive indications of increased use of underpasses. A promising method, but further documentation needed before it can be generally recommended.
Noise	Reduction	3	Phonoabsorbant asphalt used on road sections to reduce noise disturbance near roosts. Most likely beneficial but effectiveness has not been documented. Cannot be assessed with the available level of evidence.
	Deterrence	3	Positive results from one study. Vehicle speed and ultrasound attenuation may restrict the measures' suitability. Further species-specific research required to assess the measure's potential effectiveness.
Speed reduction		3	Species-specific correlations between road mortality and vehicle speed not established. However, a potentially useful method to reduce collision numbers for a range of functional groups of bat species. Probably only applicable on certain road types.
<u>Ecological mitigation</u>			
Bat boxes		4	Many non-road related conservation interventions and studies. Wide variation in occupancy rates between box types and species. Rarely used as maternity or hibernation roosts. Ineffective as replacement for removal of trees or buildings with bat roosts.
Bat houses		2	Many non-road related examples and studies. Mixed experiences with establishing bat roosts in a new building. Preserving existing buildings with roosts more effective. Recommendable if done optimally.
Artificial holes in trees		3	No reported studies of effectiveness. Long-term monitoring needed to document effectiveness.

Mitigation type	Assess-ment	Comments
Relocate tree trunks	3	Little documentation of effectiveness. Successful examples have been reported. Needs further species-specific testing and long-term monitoring to evaluate effectiveness.
Tree retention	2	Structural diversity of forest is positively correlated with bat diversity and activity. No studies of effectiveness of tree retention are available, but it is an obviously recommendable long-term conservation measure.
Habitat improvement	2	No documentation available on the effectiveness of habitat improvements on the ecological functionality of an area for bats and their population status. An obvious, potentially effective measure, but research on habitat use and effects of roads and the different types of habitat improvements is required to assess its potential effectiveness.

Generally, the use and effectiveness of mitigation structures intended to improve road permeability and guide bats safely across roads are increased if the structures are established on pre-construction commuting routes. Evaluations of attempts to divert bats from established commuting routes to safe crossing sites show ambiguous results. Preferably, the structures should be constructed to allow bats to pass the road without changing flight height or direction.

European bats show large species-specific differences in flight behaviour and typical flight height in relation to vertical structures, landscape structures and topography. The studies referred to in this report that differentiated between species clearly documented this well-known fact and indicated that the effectiveness of most mitigation measures varies between functional groups of bats. It is also evident that bat behaviour in relation to local details in the landscape, vegetation etc. should be scrutinized from a very early stage and throughout a road construction project.
Thus, road planners will always need a detailed understanding of which bat species occur in and around a project area and knowledge about their distribution, local behaviour and habitat use. Such basic knowledge is crucial to design and implement the most effective measures to mitigate road effects.

A proper maintenance strategy for the mitigation structure should always be incorporated into the general road maintenance scheme. This is necessary to maintain long-term effectiveness of the measures, and should include both the mitigation structure itself and adjacent habitats and landscape elements that may function as commuting routes. Most often, post-construction monitoring as well as subsequent adjustments is necessary to secure the proper long-term functionality of the measures. Even small details in the measures and in the surrounding landscape may substantially decrease or increase the effectiveness of mitigation structures.

Considerations on development of mitigation measures and schemes

Species-specific knowledge of bats' distribution and habitat use in a project area is required to make optimal decisions for a mitigation strategy for road infrastructures. Bats' habitat use varies seasonally, and commuting routes between roosts sites and foraging habitats will vary through the seasons. Potential road-severances of all commuting routes and important habitats must be identified during the pre-construction phase to locate the mitigation measures optimally, and to implement an adequate overall mitigation scheme that protects the local bat populations and preserve the ecological functionality of the project area. Consequently, appropriate pre-construction bat surveys will take a minimum of one year and will include repeated surveys in the project area.

As disclosed in the literature review, most studies of bat mitigation measures have aimed at describing the use of fauna passages and technical road structures rather than the effectiveness of the structures. Appropriately, detailed pre-construction surveys are often missing. Detailed pre-construction surveys against which post-construction data can be compared are vital to evaluate the effectiveness of the mitigation interventions. Furthermore, quantifiable objectives for the interventions should be defined against which the post-construction survey data can be evaluated.

More scientific, evidence-based approaches are advised for pre-construction and post-construction surveys to enable robust evaluations and the development of more effective measures strategies. Post-construction studies to evaluate the effectiveness of specific types of mitigation measures should be replicated and include control sites in the vicinity of roads or unmitigated control sites.

Mitigation measures should be in place well in advance - preferably some years - before the road opens to traffic to allow the bats to habituate to the measures. Potential in situ field experiments before the construction phase should be performed to optimize the mitigation scheme.

During the lifetime of road infrastructures, the habitat composition adjacent to the road may change. A mitigation strategy may need to include long-term landscape management. Bats can adapt to long-term changes in the landscape. However, if the immediate effects of a road are not sufficiently mitigated, there is a risk that the populations may be lost before the long-term mitigation measures such as guidance vegetation, roosting trees and habitat enhancements can become effective.

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