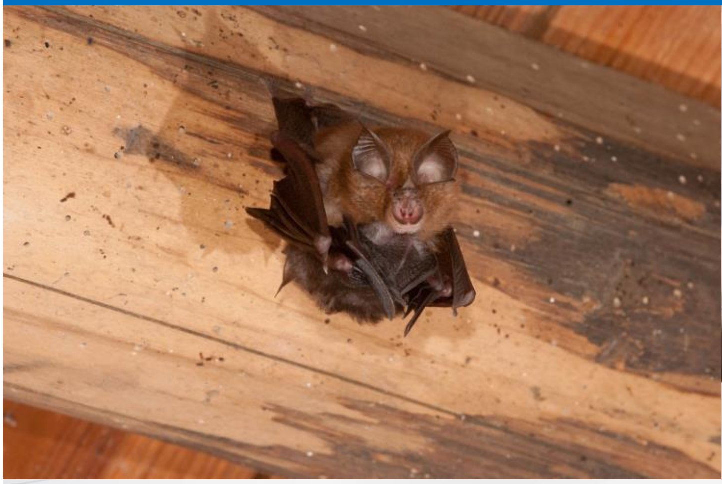
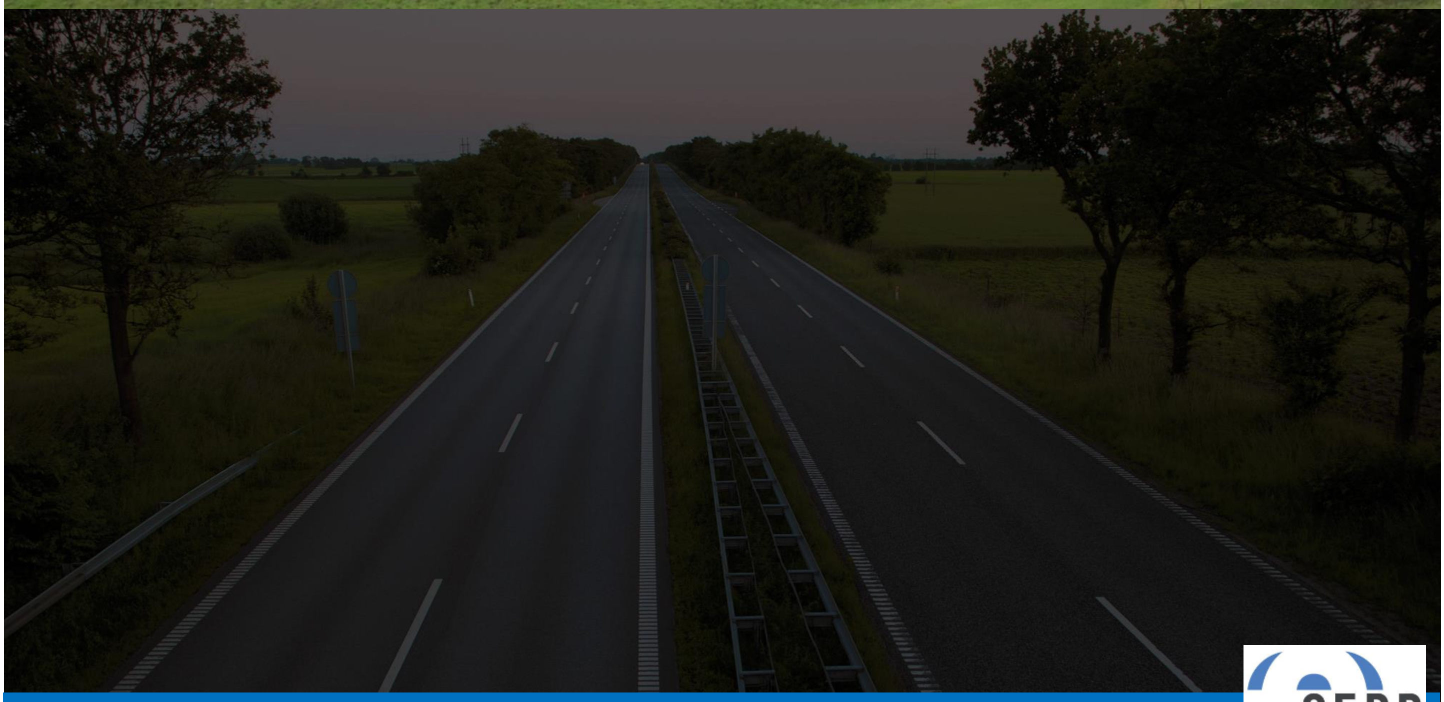
Conference of European Directors of Roads



Bat mitigation measures on roads – a guideline



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

Bat mitigation measures on roads – a guideline

Authors
Morten Elmeros, Aarhus University, Denmark
Julie Dahl Møller, JDM Consult, Denmark
Jasja Dekker, Jasja Dekker Dierecologie, Netherlands
Inazio Garin, University of The Basque Country, The Basque Country
Morten Christensen, Sweco, Denmark
Hans J. Baagøe, Flagermus Forskning & Rådgivning and the Natural History Museum of Denmark, University of Copenhagen, Denmark

PEB Project Manager: Marianne Lund Ujvári

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Executive summary

Efforts to minimise the potential impact of transport infrastructures on wildlife have become increasingly important over the past decades. Transport infrastructures have been shown to have detrimental impacts on bat and their populations due to vehicle collisions, light and noise disturbance, habitat loss and degradation, and indirectly by habitat fragmentation. To promote the development of ecologically sustainable road infrastructures with minimal impact on bat populations and to comply with legislative obligations to protect bats road agencies in several countries have published national guidelines on bats and roads.

A variety of measures have been developed to mitigate the effects of roads and traffic on bats. Bats have been observed using most of these measures as intended, but only a few recent robust studies have evaluated the effectiveness of some of the measures. The results showed ambiguous results. As a consequence, there is a limited knowledge of the effectiveness of bat mitigation measures and the shortcomings that have been documented for some measures, the currently advised mitigation strategies may not be effective.

The present guidelines aim to provide road developers, road and nature authorities, the consultancy industry and conservation practitioners with an updated guideline on best-practise bat mitigation on roads and relevant bat survey methods. The assessments and recommendations for each measure are based on an elaborate literature review of the evidence of the measures’ effectiveness.

Most studies of bat mitigation measures were descriptive and lacked adequate pre-construction data, control sites, replicates or statistical analyses to assess effectiveness properly. Only a few measures can be characterised as effective and recommendable if constructed optimally. Most of the currently advised measures show some potential to reduce the impact of roads and traffic on bats, but as their effectiveness has not been documented they should still be regarded as experimental interventions. If such measures are applied they should be monitored thoroughly to determine their effectiveness.

Generally, bat passages should conform to the local landscape and should be located on existing commuting routes to ensure high usage by bats. The structures should be constructed to allow the bats to cross roads without changing flight height or direction. Furthermore, the mitigation structures should be well-connected to bat habitats adjacent to the road. The mitigation measures should be in place and operative well before existing habitats are destroyed and 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. replacing and improving habitats and planting of trees and hedgerows. If the immediate effects on bats are not adequately 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.

Considering the limited information on the effectiveness of bat mitigation measures it is difficult to advice on the effective mitigation strategies. To change this and to improve mitigation strategies for bats, it is essential that better pre- and post-construction surveys and more robust studies of the effectiveness of mitigation measures are conducted in future road development projects.

1 Introduction

The challenge

Transport infrastructures may have a range of negative impacts effects on wildlife and the environment (Forman & Alexander 1998, van der Ree et al. 2015). The impact of roads and railways are increasingly recognised as a factor in the loss of biodiversity, and may contribute significantly to decline and loss of wildlife populations. The impact is likely to increase as road and railway networks, traffic volumes and traffic speeds continue to increase, and great efforts are made to develop more ecologically sustainable roads and railways.

Bats are especially at risk of being negatively affected by roads (Abbott et al. 2015). Most of the knowledge on effects of transport infrastructures on bat and bat mitigation measures are focussed on roads, while studies on railways are rare. However, the effects on bats from railways are assumed to be similar to the effects from roads. Consequently, the methods to mitigate the potential impacts from roads are also applicable on railways.

Road infrastructures can affect bats directly due to vehicle collisions, destruction of roost sites, habitat loss and degradation, light and noise disturbance (Russel et al. 2009, Abbott et al. 2015). Indirectly, roads may act as barriers that fragment populations and increase the extinction risk for the populations (Kerth & Melber 2009, Fensome & Mathews 2016). Bats' life history traits, behaviour and ecology make them highly vulnerable to environmental changes and increased mortality (Sendor & Simon 2003, Altringham 2011, Chauvenet et al. 2014).

All European bat species are of conservation concern. Consequently, bat conservation interests and transport infrastructure projects are often in conflict with each other. In order to develop ecologically sustainable road infrastructures and to comply with the legislative obligation on wildlife conservation, it is essential to integrate bat conservation measures when developing and upgrading road infrastructures. The conflict between bat conservation and road infrastructures has been acknowledged by road authorities, and guidelines on bat mitigation measures exist in many countries (Limpens et al. 2005, Highway Agency 2001, 2006, National Road Authorities 2006, Brinkmann et al. 2008, 2012, Nowicki et al. 2008, 2016, Møller & Baagøe 2011).

Various measures to mitigate and compensate the detrimental effects of roads have been designed and constructed across Europe. The measures have aimed to reduce road mortality, increase road permeability and compensate for roost destruction, habitat loss and degradation in order to maintain local bat populations. While many of the mitigation strategies are intuitively beneficial for bats, there is little documentation that the currently advised mitigation strategies are effective on a site specific level or on a population or landscape scale (Nowicki et al. 2008, Møller & Baagøe 2011, Berthinussen et al. 2013, Møller et al. 2016). Some of the suggested measures have not been studied sufficiently to determine their effectiveness, and they should be regarded as being only at an experimental stage. There is a great need for further development of better and more cost-effective mitigation strategies for bats.

The guidelines and how to use them

The objectives with the present guidelines are to provide road and railway developers, transportation and nature authorities, the consultancy industry and conservation practitioners with an upgraded tool box to assess and minimize the effects of transport infrastructures on bats, and to develop better and more cost-effective and ecologically effective mitigation schemes for bats.

The guidelines comprise three main parts describing:

- Relevant bat biology and species differences which must be considered when planning and developing road and railway infrastructures.
- Methods for pre- and post-construction surveys and monitoring of effectiveness of mitigation measures.
- Best practice mitigation recommendations based on reviews of published evidence of bats' use and the effectiveness of bat mitigation measures.

Figure 1 - Bats readily cross over roads and fences are no obstacle for most species, but often bats do not cross roads above traffic heights. High mortality rates may occur at road severance of bat flight paths, near roost sites and other important habitats (Photo by M. Elmeros).

2 Bats and roads

2.1 Bat biology

All bat species can be affected by transport infrastructures. The status of bat populations is very sensitive to increased mortality rates (Schorcht et al. 2009) and expansions and changes of human land use. Bats have long life spans, relatively long pre-reproduction periods, low fecundity and typically only produce a single pup each year (Sendor & Simon 2003, Altringham 2011, Chauvenet et al. 2014). Furthermore, bats use widely dispersed resources in the landscape. In one night a bat may cross several roads or railways. The location of foraging habitats and roost sites vary temporally. During the summer bats may commute several kilometres on a nightly basis between roosting sites and multiple important foraging habitats. Therefore, the complex habitat networks and connectivity across the landscape must be maintained to protect viable bat populations.

While all bat species can be affected by roads and railways, the impact varies between species. Bats show large species-specific differences in echolocation, manoeuvrability, flight behaviour and typical flight height in relation to vertical structures, landscape structures and topography (Baagøe 1987, Norberg & Rainer 1987, Schnitzler & Kalko 2001). Larger, narrow-winged species that typically forage relatively high in the open airspace appear to be less affected by roads than more manoeuvrable species that commute and hunt close to vegetation and structures. Furthermore, the barrier effect induced by roads can be significant for some of the smaller woodland species which are reluctant to cross roads (Kerth & Melber 2009, Lüttmann et al. 2010). Because of these species-specific variations in flight behaviour and habitat use, the effectiveness of mitigation measures will differ between functional groups of bats. Therefore, species-specific knowledge on the occurrence of bat species and their habitat use in a wide area along a planned road development is essential for road developers to take optimal informed decisions for a mitigation strategy.

In order for the reader to assess 1) the vehicle collision risk for each species, and 2) which bat species a certain measure could be suitable for, we have categorized some of the more common and well-studied European bat species in functional groups according to their flight height and manoeuvrability when commuting in open areas.

The larger, more narrow-winged and less manoeuvrable species usually fly high and in the free airspace away from clutter (vegetation) or man-made structures. However, even these species may also fly at low height under certain conditions in open areas, which put them at risk of vehicle collisions. Other more manoeuvrable species usually fly near or along vegetation or structures, but also fly in the open airspace. A few of these species are adapted to hunt in extremely low flight over water surfaces. These low-flying species may be at risk of collisions if they are commuting or foraging along hedgerows and forest edges parallel to roads. A third group of species are extremely manoeuvrable and prefer to hunt and commute within or close to vegetation or vertical structures. These small manoeuvrable species often follow linear or other longitudinal landscape elements when commuting, e.g. hedgerows, stone walls, embankments, forest edges, and streams (Limpens & Kapteyn 1991, Dietz et al. 2009). These ‘clutter-adapted’ species follow such landscape elements at variable flight heights, but when the bats have to cross an open stretch they tend to fly low over the surface, e.g. *Rhinolophus hipposideros* (SWILD & NACHTaktiv 2007).

Functional groups of European 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 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.

Each bat species shows a large natural behavioural plasticity. Appropriate considerations to this behavioural plasticity and local habitat use and behaviour should be reflected in the planning of mitigation strategies in road projects.

Table 1. 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

2.2 Roads and bat mitigation

Impacts

Transport infrastructures may affect bat populations in a number of ways during the construction and operational phase (Russell et al. 2009, Abbott et al. 2015). The effects of the different factors are cumulative. Hence, the effects of each individual factor do no not need to be substantial, but in combination they may have significant effect.

The effects of the different pressures and threats have different time scales (Berthinussen & Altringham 2015, van der Ree et al. 2015). Detrimental effects of roost site destruction and habitat loss and degradation occur immediately during the construction phase. Noise and light pollution will be a constant pressure when the road opens to traffic, and once roads are operational, the traffic collisions may take a toll on the populations, but these effects may take several years to detect. Similarly, the negative effects on bat populations caused by the road induced barrier effect and habitat fragmentation may take many generations to materialise. Thus, it may take many years before the full impacts on the population status are seen.

The cumulative effects and the time lag between impact and detectability of effects on bat populations should be considered when assessing and monitoring a road or railway development project and the effectiveness of the mitigation strategy.

Bat conservation and mitigation strategies

Bats are all protected under the Bonn Convention (The Convention on the Conservation of Migratory Species of Wild Animals), the Bern Convention (The Convention on the Conservation of European Wildlife and Natural Habitat) and the EUROBATS Agreement (Agreement on the Conservation of Populations of European Bats) to which most European countries have committed. In member states of the European Union all bats are strictly protected by the Habitats Directive (EC Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora).

Environmental impact assessments of transport infrastructure developments are required whenever bat populations are likely to be affected by a road or railway development. If the assessment suggests that bats are likely to be negatively affected, mitigation and compensation measures must implemented to maintain the conservation status of the affected populations and the overall ecological functionality of the project area.

The most effective method to protect bat populations is to avoid severance of commuting routes, and to avoid the destruction and degradation of roost sites and key habitats for bats, i.e. areas with a high diversity of species, populations of rare or patchy distributed species, or valuable foraging habitats. If it is not possible to avoid such areas, the road construction should include measures to prevent, reduce and offset significant adverse effects of the works on the bats and their populations. An effective mitigation strategy should result in the continued occurrence of species in the project area at the same or higher population level.

Effectiveness of mitigation measures

A number of methods have been described and implemented in Europe to reduce or offset the adverse effects of roads on bats (e.g. Limpens et al. 2005, National Road Authorities 2006, Brinkmann et al. 2012, Nowicki et al. 2016,). The measures aim to reduce road mortality, increase road permeability and maintain landscape connectivity by providing safe crossing structures. Other measures aim to reduce mortality risk by preventing the bats from crossing the roads, or by guiding the bats to safer crossing points. Habitat improvement and restoration projects have been applied to compensate for habitat degradation or loss to maintain or improve the carrying capacity for bats in the project area.

There is little evidence to show that the currently advised mitigation strategies are effective. Bats have been observed using most of the measures as intended, but bats' use of the measures have rarely been studied in depth. A few recent, robust studies have shown that some mitigation structures can be effective while others are only used by a minor proportion of the bats to cross the roads safely (SWILD & NACHTaktiv 2007, Abbott et al. 2012a, 2012b, Berthinussen & Altringham 2012, 2015).

Based on the evidence of bats' use of the mitigation and compensation measures presented in the literature, we have assessed the potential of the methods to mitigate road effects (Bethinussen et al. 2013, Møller et al. 2016). To characterise a crossing structure as effective at least 90% of bats should use the structure to cross the road safely, and the number of bat passes at the site should not be substantially lower than before the road was constructed (Berthinussen & Altringham 2015). This threshold is a precautionary figure based on the high susceptibility of bat populations to increased mortality rates, e.g. road mortalities (Schorcht et al. 2008, 2009). The reviews suggest that most of the currently applied measures are not effective and should be regarded as experimental interventions. When these measures are constructed they should be monitored thoroughly to determine their effectiveness and to help develop more cost-effective and ecologically effective mitigation strategies for road infrastructures.

Required effectiveness and population effects

It is a complex task to estimate sustainable traffic-related mortality rates, habitat losses and acceptable fragmentation for bat populations, and to define a universal criterion for the required minimum effectiveness of mitigation structures. There is a general lack of empirical quantitative data on population dynamics and effects of road and railway on bats. This lack of quantitative information hampers the application of predictive population and landscape modelling to explicitly predict the effects of roads and railways and mitigation measures on bat populations, and to define effectiveness criteria for mitigation measures. Consequently, and to comply with the conservation concerns for bats in Europe, a precautionary approach should be applied when assessing the effects of roads and the effectiveness of bat mitigation measures.

The level of the mitigation that is required to protect the status of bat populations likely varies between species, population status, habitat use, human land use and traffic intensity. At roads with a low traffic intensity, and hence a lower probability of vehicle-collisions per bat road crossing, a lower usage rate than 90% might be sufficient to sustain the local bat populations. 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, potential source populations in unaffected neighbouring areas. Contrary, a high effectiveness of mitigation measures is needed to protect population status of rare species, small vulnerable populations, or species with patchy distribution. Special consideration should be given when planning an infrastructure project in an area with occurrence such species.

3 Surveys and monitoring

3.1 Objectives

Comprehensive knowledge of bats and their habitat use in a road or railway development project area is essential to select an effective mitigation strategy. Careful and thorough pre-construction surveys of all bat species is a prerequisite for taking the correct and adequate decisions as to which mitigation measures should be applied, and to find the optimal, detailed solutions that take into account the individual behaviour of the different species.

Post-construction surveys are required to evaluate whether the potential impacts of a transport infrastructure has been adequately mitigated. Thorough post-construction surveys and focused scientific studies on the effectiveness of mitigation measures have been neglected too often but such studies are of crucial importance to test if the mitigation measures employed have had the desired effect, and are safely conducting the bats over the road.

Experts involved in the preparation of pre-construction surveys and post-construction monitoring of the impact of the road and mitigation interventions should be qualified and competent. The data and information included in assessments and evaluations should be complete and of a high quality. Reports and notes on the methodology, data and results should be publically available to allow for the exchange of the experiences and lessons learned from each project and in every country. In this way, better convergence and development of more effective road mitigation projects can be achieved more quickly and efficiently.

Field investigations of bats in road development projects are often carried out by skilful biologists from consultancies. However, they are not always fully trained in the special and difficult discipline of bat research in the field and species identification. Authorities and consultancies should always allow their employees to seek help and advice from bat specialists with an intimate knowledge of bat monitoring, and behaviour in the field and species identification.

Survey and monitoring standards (study designs, timing and schedule) are not stated in detail here as they depend on the objectives for the intervention and factors such as target species and their behaviour, population status, habitat and landscape variables.

3.2 Methods

Bat detection and species identification

Bat surveys could be made with the Site Species Richness Method (Ahlén & Baagøe, 1999), supplemented with visual observation, and studies of bat roosts. High quality ultrasound detectors with real-time full-spectrum recording capacity are necessary to record and identify bat species from their echolocation calls. Additionally, mist netting or harp trapping and radio-tracking studies should be considered in some cases, if rare and elusive species occur in the area.

The detector methods and techniques have been fully addressed elsewhere e.g. in the section on “Site Species Richness Method” (Battersby 2010). It is important to use direct detection ultrasound detectors supplemented with ultrasound recorders for automatic registrations of bats. Sufficient numbers survey nights and automatic bat detectors should be applied to record bat occurrence and activity in details thorughout the whole project area.

Direct detection and visual observation is essential for observations of flight behaviour, but is often a great help in species identification as well. Only high quality recordings will allow identification of most species. Supplementary mist netting is required to confirm the occurrence of some species. Finding and identifying all bat species in an area is a task for specialist and demands more training, self-criticism, thoroughness and time than allocated in many environmental impact assessment surveys. *Often it is the presence/absence of the rare or difficult species with small populations that makes the difference when evaluating the species richness of an area, and they play a crucial role for the right choice and correct design of mitigation measures*.

All detector registrations should be recorded and stored for later analysis, identification and documentation. It is often necesary to resurvey a site to secure additional and better recordings to confirm species identification of some of the most difficult species. Some species that are rare or difficult to identify require confirmation or identification aid by bat specialists. Guidelines for identification of bat calls can be found in: Ahlén & Baagøe (1999, 2001), Pfalzer (2002), Skiba (2009), Russ (2012), Middleton et al. (2014), and Barataud (2015).

Radio-tracking studies should be considered, particularly if a road development project affects landscapes with rare and elusive species or small, vulnerable populations in order to identify roosting and foraging areas and flight routes between these habitats.

All observations of bat behaviour and activity should be carried out in favourable, calm weather conditions. Evenings and nights with strong winds, heavy rain, fog, and low temperatures should be avoided.

To allow for analyses of effectiveness of mitigation measures, all surveys at planned mitigation sites must be controlled and quantitative, with a clear protocol which can be repeated during post-construction monitoring. Automatic ultrasound registration should be applied to collect systematic, quantitative data on bat species occurrence and activity for some of the more common species (Battersby 2010). Such surveys can allow pre- and post-construction bat activity levels to be compared in order to assess population and landscape effects of the road infrastructure (Berthinussen & Altringham 2015).

Detailed studies of bat behaviour

When sites with high bat activity have been identified in a road construction area, detailed studies of flight behaviour of the individual species should be undertaken at sites where the projected road intersects flight routes and important bat habitats. The numbers of bats of each species must be recorded quantitatively using a reproducible method to allow for comparisons between seasons, between before and after road construction at the mitigated sites and at reference sites. The detailed studies involve the use of bat detectors and visual observations. To supplement the direct visual observations, use of infrared or near-infrared video, thermographic cameras or acoustic 3D flight path tracking is recommended.

Survey period and timing

Bat activity peaks at dusk or shortly after following emergence and often continues into the night with a minor activity peak again before dawn. Bat detector surveys should be conducted during the first 2-4 hours after sunset and into the night. However, bat behaviour throughout the night at a site should be considered. Early night flight routes may differ from late night flight routes (Biedermann et al. 2014, Berthinussen & Altringham 2015). If appropriate, all-night or dawn surveys should also be conducted.

Bats' use of the landscape varies from spring to autumn depending on occurrence of suitable food resources. Consequently, bat activity at road intersections of commuting routes varies temporally. Therefore, a thorough monitoring programme of bats in a road construction project area must include separate surveys covering the whole period when bats are active:

A. At least two separate surveys in the breeding season (in the north of Europe: mid-June - early August),
B. Two separate (in time) surveys in mid-August to late-September (at least in the north) when bats disperse or migrate.
C. If certain key habitats are suspected with mass occurrence of insects in spring, an additional survey is required in late April-May. Examples are lakes, river mouths, and coastal meadows.

Two non-consecutive surveys is an absolute minimum during the breeding season. Each survey may take more than one night depending on area size (including surroundings) and habitat diversity. It is advisable to base the timing for the survey on local experience. The periods given above roughly reflect conditions in the northern part of Europe. Exact periods may vary with geographical location. In southern regions breeding seasons are typically earlier in the year and in mountain areas breeding are later than in the valleys.

Bat roost search

Trees, buildings and underground sites in a project area may house bat roosts. Surveying buildings, tree cavities and underground sites for bat colonies, day or winter roosts involve on-site inspections for roosting bats or bats found dead, signs of bats e.g. droppings, signs of "wear" around exit holes, inspections with mirrors or endoscopes, etc.
Since bats often roost in inaccessible places and signs are not always detectable, listening with bat detectors and visual observations for bat activity is often the best solution in addition to radio-telemetry. This includes observations and counts of bats flying out from the roost, recording of social sounds (incl. juvenile vocalizations), and observations when bats return at night and swarm around the entrances. Counts of bats should be recorded wherever possible.

Registration of hibernating bats is sometimes possible, especially in larger buildings or constructions such as bridges when they can be seen hanging on walls and ceilings or in fissures and cracks. In smaller buildings and tree holes they can be very difficult or impossible to register. Sometimes, if the bats are warm or semi-lethargic, a thermal camera can be a help.

Estimations of population size

Most European bat species have several roost sites, and colonies often move between roost sites between seasons and years. Colonies sometimes split up into smaller entities whereas at other times most of the population is found in one and the same roost. The individual bats in a colony may forage in different areas and change foraging habitats depending on insect availability and weather conditions (e.g. Zeale et al. 2012). This makes it very difficult or often impossible to collect valid information on population size. Most often very rough and semi-quantitative estimates are all that is possible, at least on a short year basis. For a few species and under special conditions it is feasible to obtain reliable data of actual size or trends of local populations (e.g. *Rhinolophus hipposideros*).

For common species it is possible to measure activity levels (calls per hour) and estimate relative differences in abundance before and after the road and mitigation measures were constructed. This can be done by systematic listening with automatic ultrasound detectors or systematic surveys along transects (Battersby 2010, Berthinussen & Altringham 2015). It is extremely important to try to determine if rare species are breeding in an area. For these more rare species, the potential effects could be estimated from presence-absence data.

3.3 Planning and pre-construction phase

After some decades of development of mitigation schemes for bats in relation to road constructions, it is evident that in a very large number of cases pre-construction monitoring programmes have not been adequately detailed (Møller et al. 2013). Too little effort has been allocated to searches for all bat species and roost sites in the project area, and often the variations in bat behaviour and their landscape use throughout the year has not been taken into account.

The aims of pre-construction surveys are:

- To register all bat species present in the area which are likely to be affected by the road development.
- To find all major flight routes and points where the different bat species will cross the projected road.
- To study the behaviour of each species at these potential road severance of flight paths.
- To identify important foraging habitats and roost sites in all the alternative road trajectories that are to be assessed in the impact assessment.

The pre-construction survey programme should apply robust, quantitative and standardised methods to provide data against which post-construction monitoring results and evaluations of mitigation schemes can be compared and analysed.

Therefore, it is recommended to make a clear survey protocol that compiles the information needed to conduct the subsequent post-construction surveys with the same methods. The protocol should describe in detail the applied field methods and techniques, survey sites, survey periods and timing.

3.3.1 *Planning*

A thorough planning process and pre-construction survey programme are prerequisites to select the optimal methods to minimise the impact on bats of a road scheme.

Desk studies

The first step when planning a road project is a detailed study of maps to identify potential areas with high importance for bats. A new and complete monitoring programme is almost always necessary, but a search for available knowledge and experience is often advantageous. National distribution atlases, regional fauna accounts and other publications often hold valuable information on which bats have been found in a greater area.

The qualified bat researcher must find and select all local areas and small localities assessed to be of importance as foraging areas or flight paths for the bat species occurring in the area. The researcher must also note buildings and areas with old trees that need to be investigated as possible roost sites for bats. Based on the desk study of maps and existing information on bat distribution, the qualified surveyor can plan the detailed pre-construction survey programme.

Identifying potential foraging areas and flight paths

Foraging areas: Bats are not evenly distributed in the landscape. Generally, very few bats are found in a completely open, treeless, agricultural landscape with large areas of monoculture crops. In such areas bat activity will normally – but not entirely – be limited to a few individuals (commuting or hunting) of the high-flying species such as *Nyctalus* bats, *Vespertilio murinus, Tadarida teniotis,* or sometimes *Eptesicus*, *Miniopterus* or *Pipistrellus* species. In most regions of Europe it is normally safe to pay only limited attention to such structure-less and uniform agricultural landscapes.

It is important to focus the survey efforts to landscapes and habitats with higher and more diverse insect concentrations such as deciduous forest, forest edges, hedgerows, parks, scattered trees, bushland, larger old garden areas, rivers, lakes, fiords etc. Areas with one or more of these “elements” are the ones with high concentrations of bats and with high species diversity of bats. The highest species diversity is often found in very large (1000 ha or more), heterogeneous areas with a mosaic of many of these landscape elements.

All such potentially valuable bat localities in a wide corridor along the planned road transect must be carefully monitored with bat detectors, automatic ultrasound recorders, etc. However, in complex, mosaic landscapes it is often necessary to monitor bat species occurrence and activity in an even larger area along the road trajectories in order to ensure that all species occurring in the landscape which may be affected by the planned road scheme are recorded. Small bat species regularly fly up to 5 kilometres from their colony or roost and larger species even further (Robinson & Stebbings1997, Zeale et al. 2012).

Flight paths: Studies of updated aerial photos to identify all possible sites where the road or railway trajectories will sever linear landscape elements that may function as commuting routes for bats, i.e. hedgerows, treelines, stone or rock walls, forest edges, rivers and streams, etc.

Bat roosts: Select for inspection all houses, underground sites, and old trees that could possibly contain summer roosts, (incl. maternity colonies), temporary roosts (intermediate and/or mating roosts), and winter roosts (hibernacula). It is necessary to check all houses and trees that have to be demolished or felled, and all houses or trees in the vicinity of the projected road from which bats could be commuting to and from foraging areas across the road.

3.3.2 Pre-construction

Start 2-3 years before the road is taken into use

Because of the temporal variation in bat behaviour, at least one year is needed for surveys for the impact assessment.
When the trajectory and mitigation measures have been decided, it is strongly advised *that bat pre-construction surveys at the mitigation sites and reference sites be initiated as early as 2-3 years before the road is taken into use.* It is evident that studies are needed of the behavioural response of the individual bat species to the landscape changes induced already during the early phases of the road construction. Likewise, it is clear that potentially effective mitigation measures need further refinement or in situ adjustments to increase effectiveness to an acceptable level before they can be recommended. 1-2 additional years are necessary whenever any kind of such clarifying work is needed. Finally, to have most effect all changes and developments of existing and new guiding structures in the landscape (hedgerows, treelines, stone fences, screens, etc. must be in place and have been adopted by the bats before the road is opened to traffic. Since the planning and construction phases for road and railway developments are often long, such a long-term preparation can be implemented into infrastructure projects.

Daytime inspection of the project area

The next step is visiting the area in daylight, for a detailed inspection of all selected areas and localities of interest. During the visits it is decided which sites to visit or patrol at night with bat detectors and which sites can be monitored with automatic ultrasound recorders. All buildings and old trees are inspected and those that need to be screened for the presence of bat roosts are selected. Besides, the daytime visits are often the best time to contact local landowners.

Key habitats in spring

Based on studies of maps and experience from the day time inspection, the surveyor must assess if the project area includes any localities in which “key habitats” can be suspected with mass occurrence of insects in spring i.e. whether one additional survey is required in April-May. Local conditions should determine the optimal timing of this survey.

3.3.3 Field techniques

The field survey methods include hand-held detectors, automatic ultrasound detectors, searches for roosts, etc. as described above in section 3.2. Several separate surveys are needed during the season, but the exact number of necessary surveys depends on the size of the project area, the heterogeneity of the landscape and its quality for bats.

Surveys should only take place on nights with optimal weather conditions to avoid biases due to weather related reductions in bat activity. Selected areas and habitats in a corridor along the road trajectories should be patrolled with high-quality bat detectors during the first hours after sunset, when bat activity is most intense. This patrolling must be undertaken several times on the same night to record the activity of as many species as possible. In parallel, in order to increase the number of observation sites and collect quantitative data, automatic detectors should be placed on selected sites. Time must also be allocated for return visits to clarify uncertain bat species identifications with supplementary bat detection or mist netting.

Special effort must be made at potential road severances of commuting routes (from a known or unknown roost) by the projected road trajectories. Observations at these points are crucially important from sunset until midnight, but should preferably be continued all night. Locating such sites with many bats passes is the most important, and they must be selected for detailed studies of bat flight behaviour to identify possible locations for mitigation measures.

Searches for bat have been described in earlier sections. The roost surveys are an integrated part of the separate bat surveys. As described, inspection for roosting bats in buildings and trees can be made in the daytime. Listening with bat detectors combined with visual observation of emergence from the roost in the evening, and returning in the morning and listening for social sounds are often most rewarding when it comes to species identification and estimation of numbers in the colony. If radio-telemetry studies are applied these may also identify some roosts.

Alternatively, bat roost identification can be performed with video cameras and automatic ultrasound recorders. Searches for bats in intermediate roosts are made in spring, for maternity colonies and for other day roosts are made during the summer surveys. Searches for bats in intermediate roosts or mating roosts are made in late summer and autumn depending on regional differences. Searches for winter roost are best made in winter preferably in January-February.

3.4 Post-construction monitoring

Post-construction monitoring should be performed to document that the implemented mitigation scheme for a road infrastructure has reached the target and continuously achieves the objectives of the scheme, i.e. by maintaining the viability of the bat populations affected by the road infrastructure.

The purposes of the post-construction monitoring programme are:

- To evaluate the effectiveness of mitigation and compensation measures and identify if modifications or maintenance actions are needed.
- To evaluate the impact of the road and mitigation schemes on local landscape and population scale.

An appropriate post-construction monitoring programme should ensure that unforeseen significant adverse effects from the road are identified as soon as possible and remediated. The monitoring programme should be an integrated component of the maintenance programme of the infrastructure.
The methodological approach in the programme should be robust, replicable and quantitative. The monitoring protocol should ensure results are comparable to pre-construction survey information. Preferably, sufficient data to allow statistical analysis should be collected.

Methods

The methods for the fieldwork with detectors, automatic ultrasound recorders, visual observations, searches for roosts, etc. were described above in section 3.2. The detailed studies of bats use of mitigation measures could be supplemented with infrared or thermal video camera and acoustic 3-d flight path tracking to describe bat flight patterns and road-kill surveys depending on the objectives of the monitoring project.

Surveys which are to be compared to studies from earlier pre-construction surveys should be carried out using the same protocol and at the same time of year at each site to avoid biases due to seasonal changes in bat activity.

To assess effectiveness of mitigation structures it is often necessary to adjust the observation procedures according to the new structure, i.e. observe both bat activity in a new underpass but not forget to observe bat passes over the road as well. Furthermore, bats passing another reference site on the road adjacent to the mitigation construction should be observed.

3.4.1 Effectiveness of mitigation measures

Objectives

To evaluate the effectiveness of mitigation and compensation measures by monitoring the proportion of bats that uses the measures to cross the roads safely.

Procedures

Bat passes at the crossing structures and relevant reference sites should be recorded. The number of passes per species, flight direction and height, and distance to mitigation structures should be recorded to analyse effectiveness. The survey methods should be quantitative, robust and replicable. A sufficiently high number of repeated surveys should be conducted to collect appropriate data for statistical analysis.

Bats show a large natural behavioural plasticity and adapt their behaviour to landscape changes, e.g. change to alternative commuting routes if conditions in an existing route are altered. Road-kill surveys can be carried out to identify potential unmitigated road stretches with many road-kills. To reliably detect such stretches and estimate total fatality numbers, daily carcasses surveys are required, as the persistence of small carcasses is short (Santos et al. 2011).

Standards

A high usage of fauna passages by bats must be attained to reduce road-kill numbers sufficiently, and to maintain the landscape connectivity across a road to preserve viable bat populations. To characterise a crossing structure as effective, we advise that a minimum of 90% of bats should use the structure to cross the road safely without risk of traffic collision, and the number of bat passes at the mitigated site should not be substantially lower than before the road was constructed (Berthinussen & Altringham 2015). For deterrence interventions, at least 90% of the bats should show avoidance behaviour. These values are a precautionary figure based on the high susceptibility of bat populations to increased mortality rates, e.g. road mortalities (Schorcht et al. 2008, 2009). The exact values needed to protect the affected bat populations probably depend on the species, population size and traffic loads on the road.

Other observations and considerations

Detailed records of the mitigation structure and observation of bat behaviour and flight paths and other data (e.g. weather, roost persistence, forest management) should be noted to identify potential reasons for failure of the measures, maintenance needs or methods to improve the effectiveness for specific species.

3.4.2 Impact on population and landscape scale

Objectives

To assess the impact of road infrastructure on bat abundance at landscape and population scale.

Procedures

Abundances of individual bat species are estimated as relative activity (bat calls per time unit) with ultrasound detectors at fixed monitoring locations or transects following the protocol that was also used during the pre-construction survey (e.g. Battersby 2010, Berthinussen & Altringham 2015).

A sufficiently high number of monitoring sites or transects should be monitored to collect sufficient observations to allow statistical testing of trends in bat activity.

The long-term temporal development of local populations of a few species with high roost site fidelity can be monitored by counts of colony sizes in buildings and underground sites. Great care must be given not to disturb the bats which may cause them to abandon the roost site.

Standards

Species diversity and the abundance of each species should not decline over time. If colony sizes are estimated the numbers should remain stable or even increase within the natural fluctuation of local bat populations.

Other observations and considerations

Habitat variables on monitoring sites and transects should be considered when monitoring landscape level effects to avoid biases due to habitat variations in bat abundance between surveys from variations in bat activity (e.g. Berthinussen & Altringham 2015).

4 Bat mitigation measures

4.1 Overpasses

Overpasses are constructions that facilitate safe crossings over roads at flight heights above the traffic (Iuell et al. 2003). Overpasses for bats include: wildlife overpasses, modified overbridges, bat gantries and hop-overs (e.g. Limpens et al. 2005, Brinkmann et al. 2012).

4.1.1 Bat gantries

Bat gantries are simple, narrow, linear, bridge-like structures that are constructed specifically for bats to guide them over the road at safe height above the traffic (e.g. Highway Agency 2006). The aim is to guide the bats across the road above the traffic to reduce road mortality risk and maintain landscape connectivity for the bats. Gantries are intended to provide the bats with sufficiently strong echoes so that they do not decrease their flight height when crossing the road. The designs of bat gantries range from steel wire gantries with plastic spheres at intervals, lattice constructions, and solid constructions resembling small bridges (Berthinussen & Altringham 2012, Schut et al. 2013, Cichocki 2015, Nowicki et al. 2016).

The design of the gantry is important for its effectiveness. Wire gantries are only used by a very small proportion of bats to cross a road (Berthinussen & Altringham 2012a, 2015), and other open constructions are probably also ineffective, e.g. nets and lattice gantries (Cichocki 2015, Schut et al. 2013). Large spheres with multiple reflective surfaces on the wires may provide the commuting bats with stronger echoes and increase bats' use of wire gantries. Wire gantries with large spheres installed at short distances on the wires have been proposed as a temporary measure, but better documentation (longer surveys and more replicates) is needed (Pouchelle 2016).

Bat gantries with a closed design may have a better functionality (Naturalia Environnement & FRAPNA 2015) and should be studied further. Such structures may provide bats with stronger echoes and also reduce noise and light disturbance from vehicles on the road below.

Best practice mitigation

The effectiveness of gantries is ambiguous. Generally, wire gantries are not effective and cannot be recommended. Gantries of closed designs should be used only on an experimental basis, that is, with thorough post-monitoring and adjustments to the gantry design if necessary.

- The gantry must be located exactly on an existing bat flight path.
- The gantry should be constructed so that the commuting bats do not need to change their flight height to follow the structure across the road.
- The gantry must be well connected to the surrounding landscape by means of hedgerows and trees. Gantries in forest gaps should be connect to the trees in the forest edge.
- It is not likely that the gantry will be effective if the bat passes are distributed over a wide section of the road, which can be the case e.g. in forests.

Examples of gantry designs can be seen in Abbott et al. (2015), Berthinussen & Altringham (2015) and Nowicki et al. (2016).

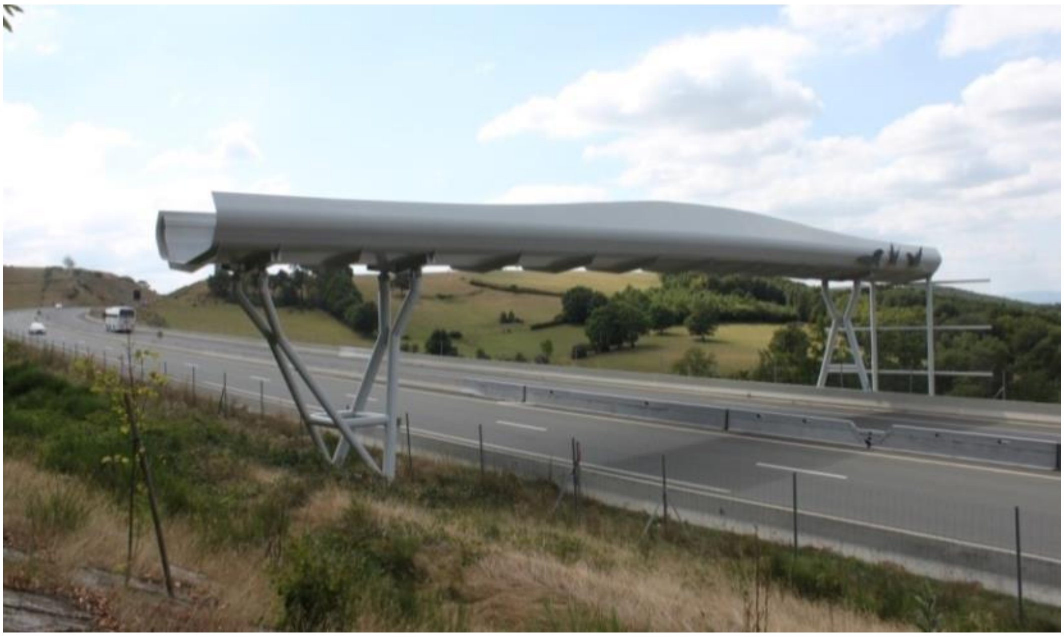

Figure 2 - Bat gantry on the A89 west of Lyon in France. The closed structure of the gantry may protect the bats from traffic noise and light disturbance (Photo by M. Elmeros).

4.1.2 Hop-overs

A hop-over consists of existing or planted trees and hedgerows on either side of a road (e.g. Limpens et al. 2005, National Roads Authorities 2006, Brinkmann et al. 2012). The tall vegetation on the road verges is intended 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 screens on the road verges. Alternatively, tall barrier screens may function as hop-overs.

Hop-overs are suitable for narrower roads. Hop-overs are best used as mitigation measure on roads levelled with the terrain or on roads in low cuttings. If a low bridge traverses a bat flight path, screens could be installed to function as a hop-over for medium- and high-flying species, which are reluctant to use underpasses (Bach & Bach 2008).

Bats have been observed using severed hedgerows as hop-overs, but the flight height of the bats or the proportion of bats crossing the road at safe and unsafe heights have rarely been noted. The height of the trees near the road and the flight height for some North American bat species have been proven to be correlated (Russel et al. 2009), and 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*, *Rhinolophus ferrumequinum* , *Pipistrellus* species and *Barbastella barbastellus* 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, Lüttmann et al. 2011, Nowicki et al. 2016).

There is a positive correlation between the height of the road verges and flight height of European bats when crossing the road (Lüttmann et al. 2011, Berthinussen & Altringham 2012, Picard 2014). This suggests that ramps or embankments along roads could reduce collision risk if bats maintain a high flight height above traffic while crossing the road.

Hop-overs may have some potential for reducing bat-vehicle collision risk for some species (*Myotis daubentonii, Myotis brandtii/mystacinus* and *Myotis myotis*) under certain circumstances, but hop-overs have not been documented to consistently increase the flight height sufficiently for bats attempting to cross the roads (Lüttman 2012, 2013, Christensen et al. 2016). Fence and screen hop-overs are ineffective for *Rhinolophus hipposideros*, which tends to fly along the fence to cross the roads at low height at the end of the barrier (SWILD & NACHTaktiv 2007). Hop-overs are probably also ineffective for other low-flying, manoeuvrable species (Group A: *Myotis bechsteinii, Myotis emarginatus, Myotis nattereri* and *Plecotus* species).

Screen hop-overs could be more suitable for less manoeuvrable, low flying species such as *Myotis daubentonii, Myotis brandtii/mystacinus, Myotis myotis, Pipistrellus pygmaeus and Pipistrellus pipistrellus* and *Barbastellus barbastella* (Lüttmann 2012, 2013, Christensen et al. 2016). However, *Pipistrellus* bats also tend to fly along the barriers, including along barriers erected at the central reservation of wide roads (Lüttmann, pers. comm., Christensen et al. 2016).

Best practice mitigation

The use and effectiveness of hop-overs is species dependent. Trees and shrubs can be used for hop-overs in combination with screens or earth banks. Hop-overs consisting exclusively of trees or shrubs require regular maintenance of the vegetation to obtain and maintain a dense structure with no gaps which bats may fly through.

- Knowledge of the species composition and their flight behaviour at a mitigation site is essential to decide on an effective design of hop-overs.
- Hop-overs should not be used for low-flying, extremely manoeuvrable species (Group A).
- Extreme caution is required if attempting to use hop-overs for manoeuvrable bats (Group B and C*),* which may have a tendency to low flight between gaps in vegetation.
- Hop-overs on roads level with the surrounding terrain would usually not be considered for less and medium manoeuvrable, high flying species (Group C, D and E).
- If the tree canopy in forest edges or hedgerows extends above the road surface on embankments and low bridges, screens on the road could be installed to function as a hop-over for medium- and high-flying species (Group C, D and E).
- A hop-over must be placed exactly on an existing bat flight path.
- The hop-over should be well connected to the surrounding landscape by existing or planted hedgerows and trees (not applicable to hop-overs on bridges).
- The hedgerow/tree line should, if possible, encourage bats to gradually increase their flight height towards the hop-over.
- Species with different manoeuvrability are likely to be present at any hop-over site. The potential pros and cons of erecting a hop-over for each species must be carefully considered.
- Hop-overs cannot be recommended for wide roads as the bats descend between the screens and high vegetation.
- The sheltered road section between hop-over vegetation may also be used as flight paths or for hunting activity by some bat species. It is important to validate that a hop-over structure is used as intended and evaluate if any unintended bat activity at the structure causes an increased mortality risk.

Examples of hop-over designs can be seen in Limpens et al. (2005), National Roads Authorities 2006, Brinkmann et al. (2012) and Lüttmann et al. (2013) (only screens).

4.1.3 Wildlife overpasses

A wildlife overpass is a vegetated overbridge constructed across large transport infrastructure to reduce mortality risk and maintain landscape connectivity for the fauna (Iuell et al. 2003, National Roads Authorities 2006, Brinkmann et al. 2012). Sometimes wildlife overpasses are combined with minor roads, forest tracks and recreational paths.

Studies of overpasses have shown them to be used by all species groups ranging from low-flying, extremely manoeuvrable species to high flying, less manoeuvrable bat species. Wildlife overpasses can effectively guide more than 90% of the bats safely across roads if located and constructed optimally (Berthinussen & Altringham 2015). Furthermore, wildlife overpasses may enable the very clutter-adapted species *Myotis bechsteinii* to overcome the barrier effect of a motorway (Stephan et al. 2012).

Vegetation on the wildlife overpass and connectivity to bat habitats adjacent to the structure is significantly correlated to bat diversity and activity on the passage (Berthinussen & Altringham 2015, Bach & Müller-Stieß 2005, Lüttmann et al. 2010), and wide overpasses seem to be more effective than narrower bridges for bats (Bach & Müller-Stieß 2005).

Best practice mitigation

Wildlife overpasses 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 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.

- Wildlife overpasses should be planted with trees and shrubs to form a guidance structure across the structure.
- The vegetation on the overpass should be connected by hedgerows and treelines to bat habitats in the surrounding landscape to guide commuting bat to the overpass.
- The vegetation takes years to develop into effective guidance structures for commuting bats. Consequently, the vegetation should be planted early in the construction phase. The planting of 3-5m high trees and fast-growing species is advised.
- The vegetation on the overpass and vegetation connecting the overpass to adjacent bat habitats must be maintained throughout the lifetime of the overpass.
- Noise and light deflecting screens should be installed along each side of the overpass to reduce disturbance from the traffic below.
- Wildlife overpasses placed across motorways in forests seem to be well used by bats. It may be an advantage if natural bat flight paths in forests, such as forest tracks, lead to the wildlife overpass.

Wildlife overpasses are widely used as a mitigation measure for larger animals. Descriptions and examples can be found in e.g. Iuell et al. (2003).

Figure 3 - Wildlife overpasses can function as a safe crossing structure for all bat species. Woodland vegetation on the overpass is important for its effectiveness (Photo by E. van der Grift).

Figure 4 - Fences and screens must be very tightly connected as even small gaps may divert the bats away from the overpass and onto the road (Photo by SWILD & NACHTaktiv).

4.1.4 Modified overbridges and other technical structures

When commuting across roads, echolocating bats may incidentally use conventional overbridges and other technical structures as passages to cross roads, e.g. road, bicycle and pedestrian bridges and road information sign gantries across roads (Abbott et al. 2012a, Ransmyr et al. 2014, Cichocki 2015, Nowicki et al. 2016). More bats may cross roads at conventional unmodified overbridges than at control sites without any technical road structures (Schut et al. 2011, Ransmayr et al. 2014), but bats only appear to use such road structures in significant numbers if the structures are located exactly at an existing commuting route.

Overbridges can be modified in a number of ways to enhance their suitability as bat crossing structures (Brinkmann et al. 2012). Panels can be installed on the side(s) of existing bridges to guide commuting bats and shelter them from street lights 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. Bats' use of overbridges increases if the bridges are modified with light deflective panels (Burette 2013, ChiroMed 2014, Picard 2014) or green verges with trees and shrubs (Lüttmann et al. 2010, NACHTaktiv & SWILD 2014).

Best practice mitigation

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 a significant effect on road permeability. However, modified overbridges could provide additional safe crossing points to the mitigation provided by purpose-build bat passages.

Modified overbridges located near existing bat commuting routes have the potential to reduce the barrier effect and mortality risk of a road scheme. If road overbridges are fitted with noise and light deflective screens as well as green verges, the overbridge could have a high potential as mitigating structure in the few relevant cases. Overbridges that are only fitted with panels seem less effective.

- Green verges can be designed on new road bridges or retrofitted on existing bridges, if the road width is reduces.
- The treelines and hedgerows planted in the green verges should form a guidance structure over the bridges.
- The vegetation on the overpass should be connected by hedgerows and treelines to bat habitats in the surrounding landscape to guide commuting bats to the overpass.
- The vegetation takes years to develop into effective guidance structures for commuting bats. Consequently, the vegetation should be planted as early in the construction phase as possible. Planting of 3-5m high trees and fast-growing species is advised.
- The vegetation on the modified bridge and the adjacent hedgerows must be maintained throughout the lifetime of the overpass.
- Overbridges with green verges should also be fitted with light and noise deflective screens to reduce disturbance from the traffic below.
- Modified overbridges with green verges or panels should be well connected to bat habitats in the surrounding landscape by hedgerows or tree-lines.
- Panels used to modify overbridges should be sufficiently high (>2 m).

Examples of modified overbridge designs can be found in Brinkmann et al. (2012), Burette (2013), NACHTaktiv & SWILD (2014) and Picard (2014).

Figure 5 - A modified road overbridge with hedgerows on the state road S170n in Germany. The vegetation is to develop further to provide a dense guidance structure. Screens on the side of the overbridge provide protection of light and noise disturbance from the vehicles on the road below (Photo by SWILD & NACHTaktiv).

Figure 6 - Retro-fitted panels to the railings on an overbridge have increased the number of *Rhinolophus* bats that commuted along an overbridge in Bourges in France (Photo by L. Arthur).

4.2 Underpasses

Underpasses are constructed specifically to facilitate safe passages for wildlife, for carrying drains or streams, or they can be designed for trains, vehicles or people (e.g. Iuell et al.

2003, Nowicki et al 2016). Underpasses comprise culverts and tunnels as well as the usually more spacious viaducts and river bridges. Bats may regularly use underpasses that are designed as wildlife passages as well as underpasses that are constructed for other purposes, e.g. tunnels for minor roads, agricultural access roads, forest tracks and pedestrian paths (e.g. Bach et al. 2004, Abbott et al. 2012a, Berthinussen & Altringham 2012).

4.2.1 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). Culverts carry watercourses or open drains under the roads. Tunnels and large culverts with dry banks on one or both sides of the stream are sometimes constructed only to function at wildlife passages, but most tunnels are constructed for purposes other than wildlife. Multifunctional tunnels and culverts can also be combined with agricultural tracks, paths for cyclists and pedestrians.

Individuals of low-flying bat species have been observed in most underpass studies. Species of this group are observed in both large, but also in relatively narrow underpasses, where higher-flying and less manoeuvrable species are only registered very sporadically in large underpasses.

Group A species such as *Rhinolophus hipposideros, Myotis nattereri, Myotis bechsteinii,* and *Plecotus auritus,* are sometimes registered in tunnels or culverts with extremely small cross sectional areas (< 2m high) (Abbott et al. 2012b, Bach et al. 2004). However, results are ambiguous and local conditions such as the presence of guiding structures and flight paths are important factors determining the use of underpasses (e.g. Berthinussen & Altringham 2012). Almost all *Myotis nattereri* and *Rhinolophus hipposideros* used a tunnel (H 2.5 m, W 2.5 m, L 25 m) that required bats to alter their flight height, whereas *Plecotus auritus* predominantly crossed above the road at unsafe heights.

Relatively low-flying species (Group B) seem to vary somewhat regarding which underpass size they will use. *Myotis daubentonii* are often registered in culverts. A culvert (H 2.4 m, W 5.6 m, L 30 m) guided 97% of *Myotis daubentonii* underneath a motorway (Møller et al. 2014). A narrow culvert carrying a stream (H 1 m, W 1.7 m, L 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 these species from tunnels with a height of 3.5 m or more (Bach et al. 2004, Kerth & Melber 2009). *Myotis brandtii/mystacinus* was found to use tunnels with height and width of 2.5 m or more (Bach et al. 2004, Berthinussen & Altringham 2015).

Pipistrellus bats have often been registered in tunnels and culverts (e. g. Bach et al. 2004, Wray et al. 2006, Lüttmann et al. 2010, Boonman 2011, Brekelmans et al. 2011, Abbott et al. 2012a,b, Berthinussen & Altringham 2012, 2015, Naturalia Environnement & FRAPNA 2015). The smallest entrance size registered in tunnels used by *Pipistrellus* bat was 2.5 m height and 2.5 m width (Berthinussen & Altringham 2015). A tunnel (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.

Eptesicus sp. and *Barbastella barbastellus,* which display both open-adapted and edge-space characteristics, have been registered flying through large tunnels (H >4.5 m, W >5 m) only (Boonman 2011, Kerth & Melber 2009). Species that normally forage in open airspace, e.g. *Nyctalus* bats are very rarely found to use tunnels or culverts (Boonman 2011, Brekelmans et al. 2011, Abbott et al. 2012a, b). 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 suggest that culverts that do not require bats to change their course and flight height seem to be more effective (Berthinussen & Altringham 2012, 2015). Some studies indicate that screens on the road verge above underpasses increase the effectiveness of the underpasses (FGSV 2008, Lüttmann et al. 2010).

Culverts are more effective than tunnels for some species (Cichocki, 2015, Naturalia Environnement & FRAPNA 2015), probably because the waterways often function as commuting routes for many low-flying bat species. Additional guidance (e.g. hedges) was not significant in explaining the use of culverts carrying waterways (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 (Abbott et al. 2012a, 2012b, Berthinussen & Altringham 2012).

In conclusion, tunnels can be used by most bats except open-airspace hunting species. Tunnels and culverts can be effective in guiding more than 90% of low-flying bat species safely under roads (Abbott et al. 2012a, 2012b, Berthinussen & Altringham 2012, 2015, Møller et al. 2014, NACHTaktiv & SWILD 2014). The cross sectional area of the underpasses – particularly the height – is a significant factor in determining which species use the underpass, and how efficient it is (Lüttmann et al. 2010, Boonman 2011).

Best practice mitigation

Culverts and tunnels can be an effective measure for some bat species. However, the effectiveness of tunnels and culverts vary markedly between species and sites.
To collect more accurate information on effective mitigation strategies, we recommend further thorough studies. A large number of the previous studies have only recorded bat activity in the tunnels or culverts, but they have not recorded crossing the road above the underpasses or prior to the road construction for comparison.

- Culvert and tunnel design should conform to local vegetation and topography, and should always be built as high and wide as possible to optimize effectiveness for as many bat species as possible.
- The underpasses should be constructed so that the commuting bats do not need to change their flight height or direction to fly through the structure.
- Knowledge of the species composition and their flight behaviour at a mitigation site is essential to decide on an effective design of underpasses.
- Culverts and tunnels are likely to be effective for bats flying at low to medium heights (Groups A, B and C).
- Large tunnels (H >5 m, W >5 m) may guide some proportion of bats flying at medium to high altitudes (Group D) safely under roads.
- Narrow underpasses (H and W <2 m) should be used with extreme caution, e.g. only for bats from groups A and in combination with watercourses.
- It is important that tunnels and culverts are well connected to the surrounding landscape by hedgerows or treelines.

Figure 7 - Bats may use multifunctional tunnels if there is little human traffic during night and minimum lighting in the underpass. The waterway should never be illuminated (Photo by M. Elmeros).

Figure 8 - Hedgerows have been planted to guide the bats into the tunnel under the state road S170n in Germany. Tall fences on the road above the underpass enhance the effectiveness of the passage for low-flying species and may function as a hop-over for species with medium and high flying heights (Photo by SWILD & NACHTaktiv).

Tentative minimum estimates for the recommended height and width of tunnels and culverts for each species group:

Group A:	H >2 m, W >2 m
Group B:	H >2 m, W >2 m over waterways H >4 m, W >4 m over land
Group C:	H >4.5 m, W >5 m
Group D:	H >4.5 m, W >5 m. Effectiveness is very questionable
Group E:	Not a recommendable mitigation method for these species

4.2.2 Viaducts and river bridges

Viaducts and river bridges 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 their large size, clearance and open structure viaducts and larger river bridges may effectively preserve existing wildlife corridors and habitats in the landscape.

Spacious underpasses are used by many bat species and individuals. There is evidence that a river bridge was effective in guiding 98% of bats (*Pipistrellus pipistrellus, Pipistrellus pygmaeus* and *Myotis* bats) safely under a road (Lüttmann et al. 2010, Abbott et al. 2012a, 2012b). Because viaducts and river bridges are often high, they have the potential to aid most species (maybe except the high-flying species in Group E, depending on the height) safely underneath a road. Viaducts and waterways are usually constructed above natural corridors and guiding structures for bats such as waterways or valleys, which increases the probability that bats will use them.

Best practice mitigation

We recommend that whenever possible, viaducts should be constructed as mitigation measures in preference to tunnels and culverts. However, attention should be paid to the collision risk for open-airspace hunting species, which may fly low across the elevated road stretch on the viaduct bridge. In such cases, placing collateral screens on the bridge (along both sides and possibly also on the central reservation between the two lanes) should be considered.

Figure 9 - Viaducts and river bridges may preserve vegetation structures and habitats used by bats as flight corridors (Photo by M. Elmeros).

4.3 Other interventions

A variety of interventions other than fauna passages are available to reduce the detrimental effects of roads on bats, e.g. reductions in habitat degradation and fragmentation due to light and noise pollution, and measures that aim to reduce road mortalities or to divert bats to safe crossing sites.

Measures that deter or divert bats away from the road will, if effective, increase the barrier effect of the infrastructure. Therefore, 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 to passages. Noise barrier screens installed to reduce disturbance of humans may also function as barriers and guidance structures for bats.

4.3.1 Artificial lighting

Artificial lighting may cause strong avoidance behaviour by some bat species and increase landscape fragmentation for bats (Stone et al. 2015, Rowse et al. 2016). The photosensitivity of bats varies between species, and depends on light intensity and spectral content. In particular low-flying, woodland specialists are most sensitive to artificial light in their habitats and commuting routes (Kuijper et al. 2008, Stone et al. 2009). High-flying species such as *Vespertilio murinus*, *Nyctalus* sp. and *Eptesicus* sp. seem less sensitive to light and often exploit the rich insect abundance around street lamps, particularly in late summer and autumn (Blake et al. 1994, Rydell & Baagøe 1996). This behaviour may increases the risk of road mortality for these species.

Artificial lighting effectively deterred commuting *Rhinolophus hipposideros* (Wray et al. 2006, Stone et al. 2009), and artificial lighting seemed to be successful in redirecting *Rhinolophus hipposideros* from an unsafe crossing site to a nearby river bridge (Billington 2013). Artificial lighting has also been shown to affect the flight patterns of *Myotis dasycneme* and *Myotis daubentonii* (Wray et al. 2006, Kuijper et al. 2008). Long term studies are needed to determine the effectiveness and potential habituation to light deterrence. Furthermore, collateral effects of installing deterring lights need to be examined, such as the potential increase of the barrier effect and habitat fragmentation caused by the road.

Artificial lighting can be modified to reduce the impact of light pollution and the barrier effect of lamp lit road sections. Amber coloured narrowband LED street lighting should be less visible and hence more tolerable toy bats than normal wideband white street lighting (Fure 2012, Rowse et al. 2016). Furthermore, amber coloured light does not attract as many insects and foraging bats as white light does (Blake et al. 1994).
A simple method to reduce light spillage from conventional street lights into the surrounding bats is to install a hood or to position the light on a short lamp pole. Light pollution from vehicle lights can be reduced with opaque screens. This should be done whenever noise screens are erected on roads adjacent to bat habitats.

Best practice mitigation

Artificial lighting should only be used as a deterrent if safe crossing sites are available nearby as the barrier effect of the road may otherwise increase. However, very little is known about the effectiveness or the negative effects of this measure. Deterrence and guidance of bats with artificial lighting should only be applied on an experimental basis and monitored.

- Artificial lighting as a deterrence is most likely to be successful for the most photosensitive species, e.g. *Rhinolophus* sp., *Myotis* sp. and *Plecotus* sp., but it may affect many other species.
- The secondary effect of artificial lighting on other species, particularly species which are known to hunt near street lights, should be carefully monitored.

Disturbance from street lamps at roads and the potentially increased mortality risk for species that forage on insects around street lights might be reduced by:

- Being very selective and critical in whether street light is needed at a road section or on/in multifunctional fauna passages.
- No light is better than any of the following three solutions to reduce light disturbance.
  - Shielding lamps or otherwise directing the light beam on the road surface only.
  - Use of dynamic lighting systems controlled by motion sensors.
  - Installation of amber-coloured light. The effectiveness of such ‘bat-friendly’ lighting to reduce any light-induced barrier effect needs to be documented.

Examples of light bollard designs to deter bats and methods to reduce light pollution of bat habitats can be found in Fure (2012), Billington (2013) and Picard (2014).

Figure 10 - The amber coloured street lighting may minimise the light disturbance of bats. Furthermore, the lamps on this path in the Netherlands are only switched on when there is a bicycle or a pedestrian on the road (Photo by V. Loehr).

Figure 11 - Lighting on this bicycle bridge in the Netherlands has been installed in the railing to reduce the light spillages into the surroundings and maintain a dark zone along the bridge to encourage the bats to use it as a safe overpass (Photo by V. Loehr).

4.3.2 Noise

Traffic noise reduces foraging efficiency for many bat species (e.g. Schaub et al. 2008, Luo et al. 2015, Bunkley & Barber 2015), and the noise seems to act as a general aversive stimulus that causes an avoidance response (Zurcher et al. 2010). Noise has been suggested as a deterrent for bats at crossing sites. Observations suggest that *Rhinolophus ferrumequinum* altered their behaviour when vehicles crossed a road section coated with a special surface (ChiroMed 2014). The noise caused the bats to evade their attempt to cross the road. The effects of audible warning road surfaces have only been tested at this one site, and the method's effectiveness has yet to be evaluated adequately.

As a mitigation measure, the audible warning system 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 sound frequencies generated by the vehicles, and bat species involved. Due to these limitations, the audible warning road surfaces might only be applicable to roads with non-continuous traffic and with a speed limit of less than 100 km/h (ChiroMed 2014).

Figure 12 - An audible warning system installed on a site with a high number of bats crossings over a 37m long road section on the regional road RD530 in France. When cars are passing patches with special porous asphalt (light patch under the blue car on the picture) a high frequency sound is generated to warn bats (Photo by M. Elmeros).

Best practice mitigation

Observations suggest that noise may deter bats and reduce mortality risk, but further examinations are needed to confirm the aversive behavioural response by *Rhinolophus ferrumequinum* and the behaviour of other species. Further studies are also needed to verify the expected reduced mortality rate and habituation of bats to the noise stimuli as seen in other mammals. If effective, audible warning mitigation is suitable on road sections in forests and open foraging habitats with no distinct crossing sites, and on roads built at the same elevation as the surrounding terrain.

More information on audible warning road surfaces is available in ChiroMed (2014).

4.3.3 Hedgerows, trees and screens

Many bat species use linear and longitudinal landscape elements such as hedgerows, treelines, rivers or streams and forest edges as guiding structures when commuting (e.g. Limpens & Kapteyn 1991). Fences, treelines and hedgerows are regularly installed or planted to divert bats away from unsafe crossing sites to safer crossing sites (e.g. Billington 2013, NACHTaktiv & SWILD 2014). Hedgerows and treelines can also be used to create a funnelling effect towards an underpass, overbridge, etc. to increase the proportion of bats that use the fauna passage. Barrier screens have been installed at road sections above underpasses to discourage bats from crossing over the road.

Guiding fences or hedgerows have been used by monitored bats, *Rhinolophus hipposideros, Myotis daubentonii* and *Myotis myotis*, in some cases guiding them to safe crossing points across a road (Britschigi et al. 2004, Koelman 2013, Picard 2014). Furthermore, an increased movement of bats along fenced road stretches has been observed (Lüttmann 2012, 2013), particularly for *Myotis, Plecotus and Pipistrellus* species. Barrier screens at the road margin above culverts may increase the effectiveness of the underpass and thus reduce road mortality at river crossings (Picard 2014).

Fences (5m high) seemed to be effective in guiding some species to safe crossing points at a railway (Flaquer et al. 2010).

Best practice mitigation

The construction of hedgerows, treelines and screens seems to have some potential as a mitigating measure, either to change the flight paths of bats, to redirect bats to safe crossing points or to keep bats from crossing the road at the site of the barrier. However, there is no evidence proving that these measures can be efficient for 90% of the bats attempting to cross a given road. As a consequence, this measure should not be used without thorough monitoring, as well as adjustments to the mitigation design if necessary.

- Hedgerows, treelines and screens are more likely to be effective to guide manoeuvrable species commuting at low to medium heights (Groups A and B), and to some degree for less manoeuvrable, low to medium flying species (Groups C).
- Hedgerows or screens intended to guide bats should be well connected to existing flight paths.
- Changing bats’ flight paths may not be an easy task. It may take years for the bats to habituate to a new flight path. Hedgerows should be supplemented by screens and/or mesh fences when newly planted to increase their effect.
- Planting of 3-5 m high trees and fast-growing species is advised. Hedgerow vegetation is usually planted as low stalks, and thus takes many years to mature into effective guidance structures for commuting bats. Vegetation should be planted as early in the construction phase as possible and could be combined with temporary screens/fences while it matures.
- Screens intended to prevent bats from crossing roads should be as high as possible (4-5 m) to keep bats from flying over them. Preferably, the screens should lead to safe

crossing points at both sides. If this is not possible, bat activity should be carefully monitored especially where the screen ends.

Figure 13 - Hedgerows and treelines are planted as a mitigation measure to link existing bat habitats and flight paths to safe crossing sites. Vegetation takes years to mature. The illustrations show a corridor established as a mitigation measure for bats one and seven years after it was planted (Photos by NACHTaktiv & SWILD).

Figure 14 - Long and high fences are needed to prevent bats access to the road surface and to guide bats to safe crossing sites. The illustrated fences are installed near underpasses on the state road S170n in Germany (Photo by SWILD & NACHTaktiv).

4.3.4 Speed reduction

Vehicle speed is positively correlated with the risk of vehicle collisions for many vertebrate taxa (DeVault et al. 2015, Farmer & Brooks 2012). No studies have documented the effects of vehicle speeds on bat road mortality, but it seems plausible that the two parameters are related in the same way as they are for other groups of vertebrates (Bafaluy 2000, Capo et al. 2006).

Speed reduction could potentially be a simple method to reduce the mortality risk for bats. Speed reduction could be used on roads where other measures are difficult to construct, e.g. on road levels with the surrounding terrain, or on roads where bat are not crossing the road on well-defined commuting routes, e.g. in forest areas and open foraging habitats with no distinctive landscape features. Speed reduction may reduce collision risk for all bat species, but the effectiveness probably differs between species. Species-specific echolocation and flight behaviour differ in how far they can detect objects and respond to approaching vehicles in time.

Best practice mitigation

Posted vehicle speed and bat mortalities appear to be correlated, but the potential effectiveness of speed reductions on bat mortality on roads has not been evaluated. Speed reduction should only be used as a mitigation measure on an experimental basis. If effective, speed reduction can be implemented on roads built at level with the surrounding terrain and on road sections with no distinctive landscape features and where bat crossings occur along longer stretches of road, e.g. in forest areas and open foraging habitats.
Reduced speed limits could be restricted to the hours from sunset to sunrise. Other methods would include installation of physical traffic calming structures, e.g. rumble stripes, speed bumps, chicanes or roundabouts.

4.4 Artificial roost sites

The construction of new roads sometimes involves the destruction of trees, buildings and underground sites that house bat roosts. Such destruction may threaten local populations, especially if it concerns well established breeding or hibernation roosts, but less so if temporary roosts are involved.

Bats show a high site fidelity to their roost sites, particularly to maternity roost sites and hibernacula (Altringham 2011). Bats have an excellent homing ability and an accurate site memory (Dietz et al. 2009, Holland 2010). Bats primarily orientates find their way by their highly specialized echolocation which only functions at shorter range. Although some bat species are good at finding new roosting sites, the bats often takes a long time (months or years) to accept the sites. 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).

A number of measures have been proposed to compensate for roosting sites that are destroyed during construction works. Basically they are of two types of procedures: 1) establishing new, artificial roosts e.g. artificial bat boxes, improving existing roost in buildings and underground sites, creating new roost sites e.g. incorporating roosting sites into bridges, and 2) relocating tree trunks with existing roosts to a new position. A key factor to help bats to find and use altered or new roosts sites is that the shape and position of the entrance to the new roost is as close to the previous roost as possible. It is important that the new roosting sites are available before the existing sites are destroyed. None of the described measures are better than maintaining existing roosting sites.

4.4.1 Bat boxes and houses

Bat boxes are widely applied as conservation intervention and for research purposes (Marnell & Presetnik 2010, Korsten 2012, McAney & Hanniffy 2015). Installing bat boxes in trees and buildings is an easy and low-cost measure. Bat boxes have also been used to compensate for the destruction of bat roosting or hibernation sites by road development projects.

Numerous studies of bat box schemes have tested various bat box designs (e.g. Beck & Schelbert 1999, Korsten 2012, Rueegger 2016). The general conclusion in all the reviews of effectiveness and use 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). Although bat boxes may be occupied quickly as temporary roost sites, it often takes several years before they are regularly occupied and used for breeding (McAney & Hanniffy 2015).
Some 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). Occupancy rate of bat boxes are negatively affected by the proximity to roads up to 1000m (Christensen 2015, McAney & Hanniffy 2015).

Some small bat box projects have been successful in displacing maternity roosts of certain bat species, e.g. *Pipistrellus pygmaeus* from inside a building to large bat boxes on the same or neighbouring building (J. van der Kooij, pers. comm.). 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). The authors assessed that a determinant factor for the success of these box schemes was that the boxes were placed where bats were already roosting. Consequently, comparable successful results may be difficult to obtain in most road projects, as the trees and buildings housing the bat roosts are normally completely removed, and compensation roosts established at other locations.

An alternative to bat boxes is purpose-build new buildings and underground roost sites (Marnell & Presetnik 2010, Korsten 2012). Large structures are often better as the interior microclimate is more stable, but as with the boxes it may take some time for the bats to find the new roosting sites. Buildings and underground sites are suitable as long-term compensation actions. Protection and renovation of existing roosts in buildings and underground sites is preferable to new installations. Adaptations and improvements of existing buildings and bridges may have immediate effects as the bats already know the sites.

Best practice mitigation

Bat boxes are widely applied as conservation intervention and for research purposes, but bat boxes cannot be recommended as compensatory measure for roosting sites that are destroyed by road construction. Therefore great care should be taken to preserve bat roosts and avoid removal of known and potential bat roost structures.

- If bat boxes are installed, monitoring should always be conducted to determine if they have fulfilled their purpose and to ensure that the boxes are still in place.
- Bat boxes should be installed well in advance (preferably several years) of removal of existing roost sites.
- Wooden bat boxes typically need to be replaced every 3-5 years.
- The 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).
- Bat boxes in bridges should be installed so the vehicle collision risk is minimal for the bats when commuting to and from the roost sites
- Bat boxes should never be used for permanent ecological mitigation, but only as a temporary measure until other habitat enhancements become effective.

Figure 15 - A variety of bat box designs have been used for conservation and research purposes. Bat boxes are not recommendable as compensation for destroyed roost sites as the occupancy rate is generally low (Photo by M. Christensen & J. Dekker).

Figure 16 - Renovating existing buildings with bat roosts can be an effective method to maintain bat populations (Photos by V. O'Malley).

4.4.2 Bridges as roosting sites

Roosting bats have been recorded in bridges in many European countries (e.g. Smiddy 1991, Billington & Norman 1997, Beck & Schelbert 1999, Pysarczuk & Reiter 2008, Amorim et al. 2013, Ouvrard 2013, Gottfried & Gottfried 2014, Harrje 2015). Cavities, gaps and crevices in both old and modern bridges may resemble the conditions occurring in natural roosts for many bat species. Depending on climatic conditions, a bridge can serve as a roosting site for bats throughout the year or for parts of the year. 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 successfully been maintained or retrofitted with mitigation structures to accommodate bats (Beck & Schelbert 1999, Billington & Norman 1997, Heijligers 2005, Ouvrard 2013). Focused management of bridges have successfully maintained and even improved roosting conditions (estimated from colony sizes) during renovation work at large, old bridges. Improvements and adaptations have incorporated the installation of rough walls in roosting chamber or boxes in cavities in the bridge abutments. These management actions have maintained maternity and hibernation for species as diverse as *Nyctalus noctula, Pipistrellus pipistrellus, Myotis myotis, Myotis nattereri and Myotis daubentonii*.

Bat roosting opportunities have been built into new bridge constructions in The Netherlands as well as in the UK (Billington & Norman 1997, Heijligers 2005, http://www.dearchitect.nl/projecten/2015/detail/vlotwateringbrug/vlotwateringbrug.html), but there has been 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.*

Best practice mitigation

Addition or modification of bat roosts in bridges is a promising mitigation measure where bats are already present. As roost design seems to be highly dependent on existing conditions, no specific procedure is likely to work in every case. New or modified roost sites need to be continually monitored and adjusted if necessary over several years as experience shows that small design flaws can cause high bat mortality.

An obstacle posed by new 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 designing artificial roost sites in bridges.

Examples of bat roosts in bridges can be found in Billington & Norman (1997), Beck & Schelbert (1999), Amorim et al. 2013), Ouvrard (2013) and http://www.dearchitect.nl/projecten/2015/detail/vlotwateringbrug/vlotwateringbrug.html

4.4.3 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. Very little testing has been carried out on this method, and there is so far no evidence of its effectiveness.

Best practice mitigation

As there is no knowledge on the effect of creating artificial holes in existing trees, this are needed to determine their use by bats over several years, determining different species preferences to cavity size and shape, and investigating optimal carving/drilling procedures. Because we only partly understand all of the parameters that determine a good (maternity) roost for each individual bat species, it is important to experiment with a range of different solutions.

4.4.4 Translocation of tree trunks

Translocation of tree trunks with bat roosts has been suggested as a last resort to preserve the roost, if the tree cannot be saved (Limpens et al. 2005). 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 is dug into the ground, but this method is likely to shorten the lifetime of the trunk considerably.

Figure 17 - Translocation of tree trunks with cavities have been used an alternative to bat boxes. The microclimate in translocated tree trunks may be more suitable for bats than in bat boxes (Photo by M. Elmeros and H.J. Baagøe).

Only one study has reported of a successful relocation of a tree trunk that maintained a maternity roost of *Nyctalus noctula* (Damant & Dickins 2013). The method therefore needs much more research and further 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.

Best practice mitigation

Translocating tree trunks is a highly invasive measure and it should 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 which use eavesdropping when locating new potential roost sites, e.g. *Nyctalus noctula*.

4.4.5 Tree retention

The occurrence of large, mature trees with a high potential for natural cavities for roost sites is low in many forests. Suitable tree cavities for roosting sites might be a limiting factor for bats in modern forests. Protection of single trees or broadleaved forest stands to develop or retain a diverse forest structure containing several old decaying trees may compensate for roost site destructions and habitat degradation and loss.

Best practice mitigation

No studies have been conducted to evaluate tree retention in forests near road constructions as a compensatory measure. The method is an obvious recommendable long-term conservation measure, but it may be difficult to assess when a sufficiently large number of trees or forest stands has been protected to compensate for the destroyed roost sites. Depending on the age of the protected trees and forest stands and their potential for cavities, short-term measures may also be needed as a supplement.

Figure 18 - Protection of large trees in forests may improve long-term availability of roosting sites to compensate for the destruction of potential roost trees during road or railway development (Photo by H.J. Baagøe).

4.5 Habitat improvement

Habitat improvements are applied to compensate for habitat loss and degradation caused by the construction of roads (Limpens et al. 2005). It can consist of construction of or improvement of habitat quality of ponds or wetlands, afforestation, planting of trees and hedgerows and insect-rich grassland habitats. Intuitively, habitat improvements would increase an area's carrying capacity for bats to off-set the detrimental effects of the road development. However, there is a general lack of studies evaluating the effects of habitat improvements for bats around roads.

Creating artificial ponds seems to be an efficient way to increase feeding areas for certain bat species (e.g. Stahlschmidt et al. 2012). However, annual monitoring has shown a slow increase in use by *Rhinolophus hipposideros* of new feeding habitat in Wales (Wyatt 2010). 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.

Best practice mitigation

Habitat improvement is the only compensation measure which can compensate for the loss of feeding areas or general habitat loss and degradation. It is potentially effective, but there is a general lack of knowledge, particularly as to which habitat features are most important to maintain populations of different bat species.

Furthermore, quantitative knowledge on the size and habitat quality that are required to compensate for increased road-induced mortality or habitat losses is completely nonexistent. Studying the detrimental effects of road construction and the potential positive effects of habitat improvement requires monitoring over a long period of time

Habitat enhancements and restorations should be developed and in place well in advance of the destruction or degradation of habitats. Habitat management actions may take many years to develop into suitable bat habitats and it may take years for the bats to find the new feeding grounds or roosting areas.

5 Conclusion & perspectives

The present guidelines aim to provide road developers, nature authorities, and ecological consultants with revised and updated guidelines on best-practise for bat mitigation on roads and relevant monitoring methods for bats.

A variety of measures has been described, recommended and implemented to reduce or offset the adverse effects of transport infrastructures on bats across Europe, and road agencies in many countries have developed guidelines to reduce the conflict between bat conservation and road development in the past decades (Limpens et al. 2005, Highway Agency 2006, National Road Authorities 2006, Brinkmann et al. 2008, 2012, Nowicki et al. 2008, 2016, Møller & Baagøe 2011).

However, until a few years ago there has been only limited focus on thorough and adequate testing of whether the mitigation measures had the desired effect of actually helping the majority of individuals of the bat populations present in an area safely cross dangerous road constructions (Nowicki et al. 2008, Berthinussen et al. 2013). Møller et al. (2016) reviewed all available studies on bats and road mitigation measures in Europe to evaluate the documentation for their use by bats, assess the effectiveness and outline the level and quality of all available information on bat mitigation measures.

Bats have been observed using most of the installed types of measures as intended. However, Møller et al. (2016) showed that most of the reviewed studies of bat mitigation measures were descriptive and lacked adequate pre-construction data, control sites, replicates or statistical analyses to assess effectiveness properly. Only a few measures were assessed as unequivocally effective and recommendable. Most of the currently advised measures show some potential to reduce the impact of roads and traffic on bats, but as their effectiveness has not been documented, they should still be regarded as experimental interventions. Whenever these methods are applied they should be monitored thoroughly to determine their effectiveness and if needed detailed studies must be made to improve their functionality.

Further details on the effectiveness, advantages, constraints and uncertainties for each mitigation type and variations in their performance for different species are discussed in Berthinussen et al. (2013) and Møller et al. (2016). As a consequence of the limited evidence of the effectiveness of most of the measures, and the shortcomings that have been documented for some measures, many of the currently advised mitigation strategies may not be effective (Berthinussen et al. 2013, Møller et al. 2016).

Table 2 summarise the conclusions concerning assessments and recommendations for each measure based on the elaborate literature review of the evidence of their effectiveness (Møller et al. 2016).

As a consequence of the limited evidence of the effectiveness of present mitigation and compensation measures, the number of effective and recommendable measures is limited. Only three mitigation methods can be recommended if they are properly constructed and located: wooded wildlife overpasses, modified bridges with green verges planted with shrubs and trees, and viaducts and river large bridges. We still advise to carry out post-construction surveys to ensure that the individual measures meet the objectives and target values for the relevant bat species.

Other interventions may have some potential if implemented carefully, but they need improvement and further research to document their effectiveness test if they can be recommended for use (table 2).

To change the current situation and to develop more effective mitigation strategies for bats, it is essential that better pre- and post-construction surveys and more robust studies of the effectiveness of mitigation measures are conducted. In the present guidelines we give suggestions for such more detailed studies and experiments in situ. Furthermore, the importance of sharing and discussing results and experience from such monitoring and research is advised.

The bat species are different in biology, including flight behaviour, habitat and landscape use. The guidelines include a section outlining the complex biology of bats which must be considered when designing survey protocols and selecting optimal mitigation actions. Some bat species are very difficult to detect with ultrasound detectors. Detection of rare or elusive species with small populations is essential when evaluating the species richness of an area, and they play a crucial role when selecting the optimal types and design of mitigation measures. It is important to reserve enough time (often 2-3 years) for proper pre-construction monitoring and in situ experiments with bat behaviour at planned mitigation sites an early phase during the road construction.

Bat populations are very sensitive to increased mortality rates, habitat changes and landscape fragmentation by road infrastructures. In view of the limited knowledge on the effectiveness of bat mitigation schemes and to comply with the conservation obligations for bats, a precautionary approach is advised when developing roads and mitigation schemes for bats.

Table 2. Assessment of measures and their potential effectiveness to mitigate road impacts on bat species flying within or near vegetation and surfaces, and species flying in open airspace (see Tab. 1).

1/ A recommendable intervention if located and constructed correctly. Good evidence of use or effectivity.
2/ A potential effective intervention which shows encouraging results. Further studies required to document 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 proven to be ineffective or has shown very ambiguous results. Not recommendable.

Mitigation method		Assessment: In or near vegetation and surfaces	Assessment: Open-airspace	Notes
Fauna passages				
Wildlife overpasses		1	1	
Modified bridges	Green verges	1	1	
	Panels	3	n/a	
Bat gantries	Open structures	4	4	
	Closed structures	3	3	
Hop-overs		3	3*	Species dependent
Viaducts & river bridges		1	2	Dependent on height
Tunnels & Culverts		2**	4	
Other interventions				
Hedgerows & tree lines		2	3	
Barriers		2	3	
Artificial lighting	Deterrence	3	3	Species dependent
	Adaptation of spectrum	3	3	
	Restriction of spillage	2	2	
Audible warning		3	3	Species dependent
Speed reduction		3	3	
Ecological mitigations				
Bat boxes		4	4	
Bat houses		2	2	Very variable success rates
Relocate tree trunks		3	3	Species dependent
Artificial holes in trees		3	3	Only long-term potential
Tree retention		2	2	Only long-term potential
Habitat improvements		2	2	

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

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