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Determinants of the Performance of Bat Gantries Installed to Carry Bat Commuting Routes over the S3 Expressway in Poland

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Abstract: In road construction, environmental protection issues often become a challenge, both in the case of new routes and the existing network expansion projects. A number of specific issues are involved in severing of bat commuting routes and the relevant mitigation measures are still in the experimental stage. One of the measures are bat gantries installed on the established bat flyways aligned with the linear features of the landscape used by bats for echolocation calls, which is an example of the structures installed near Szczecin in Poland. The bat activity surveys revealed different levels of acceptance of the respective structures. The available studies identify the following factors as being relevant to relocated or modified commuting routes: road traffic volume, traffic noise, and light pollution. The article discusses which factors are the most likely to have a significant bearing on accepting specific structures by bats. The analyses show that a gantry structure can turn out to be acceptable to bats even on a completely new route if the landscape features are symmetrical and friendly to bats on both sides of the road and on both sides of their flyway as well. Conversely, without such a symmetry along the approach section, the structure may fail to perform.

Keywords: bats; gantry structures; bat activity surveys; road lighting; traffic noise

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1. Introduction

Bats are mammals whose forelimbs form wings (*Chiroptera*). The order of *Chiroptera* is divided into two suborders: *Megachiroptera* (fruit bats) and *Microchiroptera* (insect-eating bats). Bats are distinct from other mammals because of their ability of powered flight. A majority of the bat species are nocturnal animals. Hanging upside down—a peculiar posture bats assume during winter hibernation—is caused by the specific anatomy of their hind legs [1]. As insectivores, bats are considered allies of farmers and foresters [2,3]. The Spanish guidelines ([2], Appendix 22, p. 109) put it straight that: "bats play a major role in protecting biological diversity." Taking into account the above facts and relatively small populations of different bat species, a number of rules and measures are currently in place to protect them [1,4].

The bat protection guidelines defined in References [2–4] require, without limitation, that:

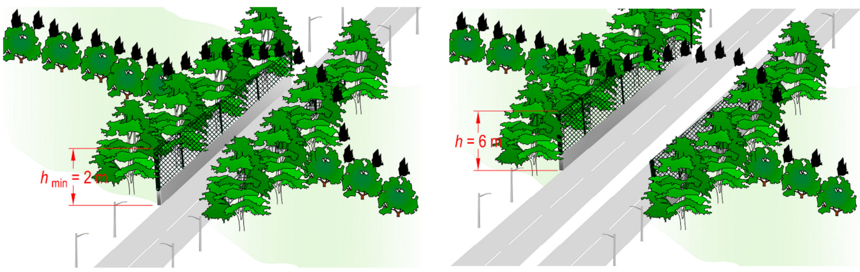
- new artificial nursery roosts are provided or the existing ones are maintained (including adaptation of pre-war bunkers and air-ride shelters to serve as winter roosting sites),
- the timing and methods of construction, repair, and other works do not interfere with the bat breeding and hibernation periods,
- observation and recording (monitoring) schemes are in place, covering roosts, refugees, and populations.

Bats are very helpful to humans and their protection is a major environmental issue [1,3–9]. These small mammals play a very important role in limiting the populations of pests and insects and also pollinate and spread plant seeds [10]. As such, they must be considered a very important asset of the natural environment. Factors harmful to bats include overuse of chemicals, which is noted more frequently these days, which is aggravated by the use of very toxic pesticides and timber fungicides. Moreover, old deciduous forests that provided foraging and nursery roosting sites for some bat species have largely vanished or at least have become degraded. The changes in the social and urban environment have made bats look for new shelters after co-habiting with men for centuries. In the past, spaces such as shacks, damp cellars, lofts, farm buildings, and church towers were frequently used by huge numbers of bats as winter roosts. However, currently, occupied buildings are weatherproofed and insulated (including lofts and cellars), which drives off bats to other potential roosting areas, such as caves, tree hollows, abandoned military bunkers, and air-ride shelters, spaces under bridges, and inside disused wells, i.e., any space where ambient temperature is sufficiently low to enable them go into winter hibernation.

This has been one of the causes why we can find tens of thousands of bats hibernating in pre-war disused German fortifications, bunkers, and air-rider shelters. Besides the above-mentioned alterations to buildings, bat habitats are often disturbed by construction of new roads, motorways, and railway lines, which, by crossing their flyways, many cut them off from their foraging or winter roosting sites. In Poland, pre-war German bunkers are converted to bat habitats as a compensational measure in the case of new road construction projects [11]. Similar compensation is provided in Ireland [3]. In other countries, adjacent tree stands are adapted to increase their bat winter roosting capacity as compensatory remediation for habitat losses related to road construction projects [12,13]. Such replacement roosts are made by attaching parts of cleared trees, which include natural hollows to the trees that are to remain in place or by making artificial hollows in completely sound trees. While these measures may turn out beneficial, their performance has not yet been confirmed and, as such, they should be monitored and used only with caution.

Taking the above aspects into account, we can state that the sustainable design of roads must include bat-related compensatory remediation. The computing routes of bats cross both the existing and planned roads. The key consideration to be taken into account when designing bat bridges is to ensure appropriate flight height across the road. Hence, the design must be preceded by an environmental survey and the flyway must be precisely determined by a chiropterologist for the observed species. Any built structures located within the flyway should be designed by taking into account this height and, moreover, adequate crossing structures should be provided to prevent collisions between bats and cars travelling down the road.

The importance of the road, the level of service, and the vehicle composition of traffic must all be carefully analyzed [14] since there is a direct relationship between the minimum vertical clearance of the road and the bat passage height. On single two-lane carriageways of lesser importance, hop-overs, which are a natural type of crossing, should be designed [4,7] comprising appropriately shaped groves of adequate height to suit the flyway of the bat species concerned (Figure 1a,b).

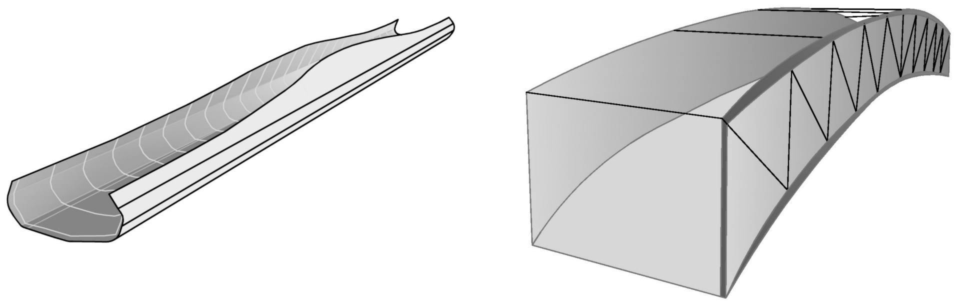


(**a**) (**b**)

Figure 1. Evolution of hop-over crossings, unlit along the length of the mesh fence (graphical representation based on French guidelines [7], (p. 42) of the following minimum heights: (**a**) on single, two-lane roads—h_{min} = 2 m or higher if required by the bat species concerned or (**b**) h = 6 m high on dual carriageway roads.

In recent years, various measures and structures have been tested on the crossings between bat flyways and roads to encourage bats to raise their flight height above the minimum clearance height of the road. The design and guidelines for use of such structures are detailed in References [2,4,7,8,15,16]. In the Netherlands, hop-overs presented in Figure 1a, without mesh fences, were initially recommended for roads of lesser importance and were found effective for almost all species except for *Rhinolophes*. This species tended to lower the height of flight at the median when a double height fence was provided, where bats were meant to cross the road. Therefore, the French guidelines recommend using 6-meter high wire mesh fences (Figure 1b) [7] both for dual carriageways and for roads of lesser importance wherever the presence of *Rhinolophes* was confirmed by the field survey.

Besides hop-overs, i.e., natural type crossings, various types of built structures are tested in different countries as compensational mitigation measures. An example of such experimental structures are unique spherical structures installed in two places over the A89 motorway near the town of Balbigny in France (Figure 2a) [17,18] whose design process included multiple changes and adjustments in relation to earth retaining and vibration damping elements, service lifetime of materials, and the drainage system design. The structural details and engineering challenges are as presented by Riou in Reference [17]. The bat flight pattern was meticulously examined using a thermal imaging camera [16]. The camera lens was positioned facing the side of the spherical shell structure to record the flight path along the structure and face the outlet to observe the flight paths inside it as well as to assess the flight path clearance for flights outside the structure. The footages were analyzed to confirm previous observations made on crossings with steel structures located in England [19] where bats followed a sinusoidal path along the structure, except that the specific spherical shape of the analyzed structure considerably increased reverberation over the median, i.e., halfway along the passage length [18], which most probably was the cause of slightly raised flight height over the second carriageway. Flights beside the spherical shell structure were noted in many cases when the bat chose not to cross the road or continue foraging activity [18]. The final conclusions section of the report [18] suggests the need to verify the performance of spherical shell structures by regular monitoring. The experimental applications in Great Britain include steel structures [19–21] and mesh enclosed bridges suspended from trees [22]. However, they are no longer used due to the reported poor performance [21]. Gaps in the corridor right at the structure were considered one of the causes.



(**a**) (**b**)

Figure 2. Graphic presentation of modern bat bridges: (**a**) spherical shell (pictured on the basis of Reference [17]). (**b**) Covered bridge of the box-profile mat finished steel sheet (pictured on the basis of Reference [23]).

Another example of special structures are single-span bridges fully enclosed by corrugated sheet cladding installed in Germany over the Biberach by-pass (Figure 2b) [23,24]. They were mounted fully by crane in two crossing locations. Their side walls are ca. 4 to 5 meters in height. The troughed cladding, mat finished in grey is fixed to steel lattice frame making up a sealed enclosure. A number of follow-up surveys were conducted by the environmentalist Jürgen Trautner [24] who used, besides ultrasound recording, night-vision devices and infrared cameras. The survey results confirm satisfactory performance of this crossing solution [24].

Problems related to environmental compensation are typically involved in motorway and expressway construction projects. Bearing in mind the above-described structures and their shortcomings, follow-up monitoring should be implemented for any new solutions designed to guide bats across roads in order to determine the crossing point performance on a case-by-case basis. This is because a structure that performed well at one place, as confirmed by a follow-up survey, can fail to perform at another.

Let us take, as an example, the environmental challenges encountered during construction of the S3 expressway in Poland, which crossed the flyways to winter roosts in a forested area near Szczecin. As far as commuting routes of bats are concerned, Puszcza Bukowa, which is a special protection area, was found to be of prime importance. It is a large forest that surrounds the south-eastern part of Szczecin. As part of environmental compensation, bat gantries were provided on three bat commuting routes severed by the planned expressway. The monitoring scheme was implemented from 2010 to 2012. The results showed varied use frequency between the structures in the consecutive years [25–27]. During the analysis of the available survey data, it became apparent that, in order to establish why a given structure performs well at one location and much less at another, it is necessary to have determined the effect of the relevant parameters of the road (further called determinants) on the frequency of commuting of bats. This relationship is the subject of analysis of this article.

2. Analysis of the Commuting Routes of Bats in the Puszcza Bukowa Forest Before and After Construction of the S3 Expressway

The commuting routes of bats to 13 pre-war bunkers were monitored by chiropterologists before and during the S3 construction project. These bunkers provided winter roosts after their adaptation for this purpose by the Mopek bat conservation association [11,26]. The commuting routes of bats before the S3 expressway construction are presented in Figure 3. The first of them was located at the verge of Puszcza Bukowa ca. 630 m from the A6 motorway (Figure 4). The middle one crossed a wide forest opening (Figure 5). The last of the three routes was located ca. 1800 m from the A6 motorway, which was also at the verge of the Puszcza Bukowa forest (Figure 6). Figure 7 presents the pre-construction and post-construction commuting routes across the S3 expressway with the bat gantries designated as 1, 2, and 3, and, additionally, two wildlife underpasses constructed on the severed forest tracks were designated with the symbol typically used for road structures.

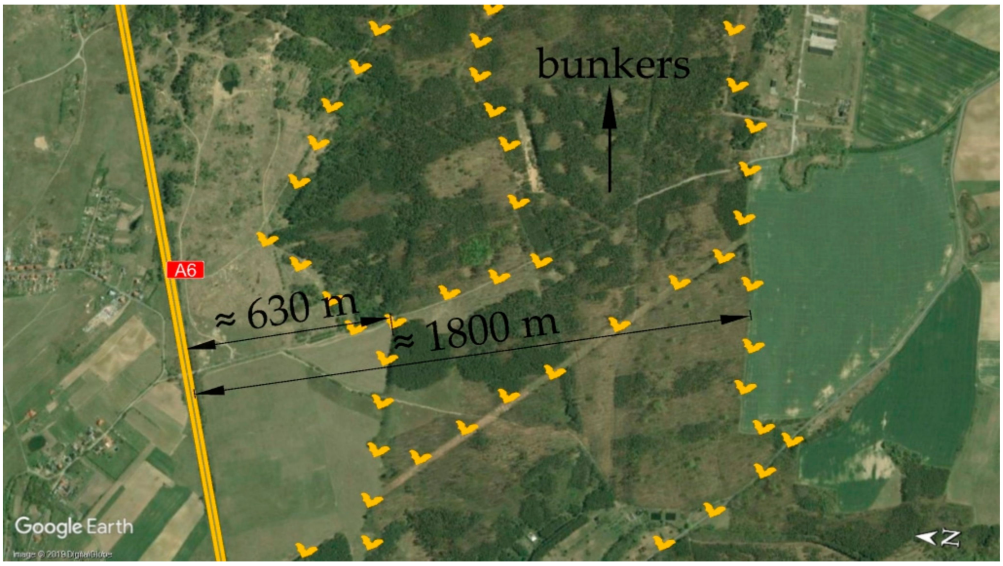


Figure 3. Commuting routes of bats before construction of the S3 expressway section across Puszcza Bukowa forest based on References [11,16] drawn on the Google Earth map [28]).

Figure 4. Bat gantry No. 1 over the S3 expressway built in the course of the flyway along the edge of forest near the interchange connecting A6 motorway and S3 expressway (the three-level interchange is visible in the background).

Figure 5. Bat gantry No. 2 over the S3 expressway built in the course of the flyway crossing the forest opening area.

Figure 6. Bat gantry No. 3 over the S3 expressway built in the course of the flyway along the forest edge.

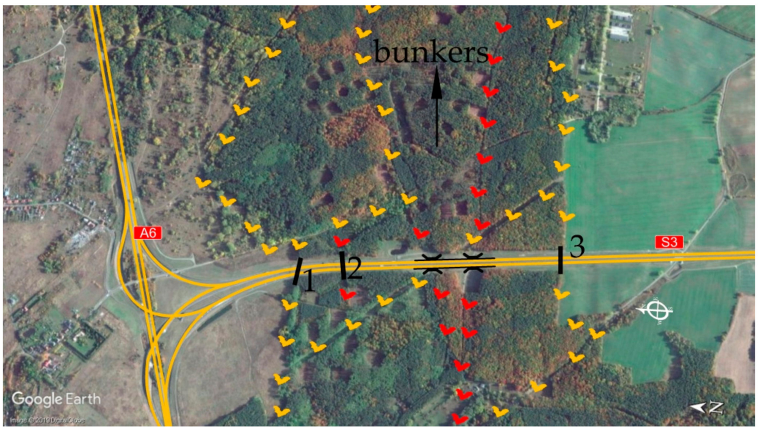


Figure 7. Commuting routes of bats after completion of the S3 expressway (drawn on the Google Earth map [28] on the basis of References [11,25]).

Significant flight route diversions occurred within the Puszcza Bukowa forest. The two main commuting routes along the forest edge that were identified during the pre-construction survey defined the locations of two bat gantries designated No. 1 and No. 3 (see Figure 7). Two underpasses were built on two local asphalt paved forest tracks and they were also appropriated by bats as part of their flight route already at the time of the expressway construction. The bat activity surveys conducted both during and after construction [25–27] showed that, in the thin part of the forest bats, created a new flyway on which the third gantry structure was built, designated as gantry No. 2 (see Figure 7). The new commuting routes are marked in Figure 7 with red symbols of bats.

Several research and post-construction surveys were carried out in the project area [26,27]. According to the survey data [26,27] in March, the greatest number of flights was noted over the third gantry, which is most distant from the interchange. However, taking into account all the surveys, the greatest number of flights was recorded over the second gantry. The least number of flights was recorded over the first gantry. Figure 8 shows the aggregate values [26,27] from the corresponding dates and hours of the 2010–2012 bat activity surveys. From the descriptions provided in References [26,27], it transpires that bat movements in the vicinity of gantry No. 1 were, for some bat species, associated with their hunting grounds and, in some cases, bats diverted from the path right above the structure or flew next to it all the way. In the summer months, passes over gantry No. 3 were related to foraging activity only in the case of a few species, with the majority of the flights being related to the linear landscape feature. Conversely, most of the flights over gantry No. 2 were related to linear landscape features used by the bats for commuting and migration. Only in March, flights related to foraging were noted over gantry No. 2 in the case of two bat species (*Nyctalus noctula* and *Nyctalus leisleri*) [26].

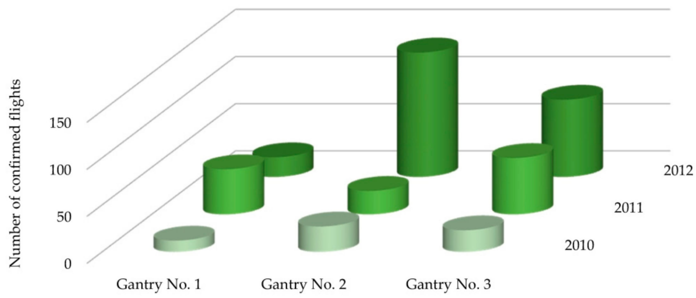


Figure 8. Results of bat activity surveys in the period of 2010 to 2012 given in References [26,27] (in selected corresponding days of the year and observation times).

The analysis of the bat activity survey data shows that, in the initial period of operation of the S3 expressway operation, bats discarded their existing commuting routes, as it has been additionally confirmed by other researcher data [18–21]. Severing of the linear elements of landscape located on the established commuting routes in relation to the construction works, including clearing of trees, disturbed the bat movements, which resulted in unsatisfactory results of environmental monitoring. In 2011, the former routes were re-established only to a small extent along the forest edge, i.e., over structures No. 1 and No. 3. The re-established routes result in an almost triple, yet still below expectations, increase in the number of confirmed passes. From the evaluation of the survey results [26,27], one can see the difficulty in interpreting the observations and obtaining conclusive confirmation of the performance of the structures as a linear feature of the landscape. The conclusions of the bat activity surveys given in reports [26,27] are in agreement with the conclusions from observations given in References [18–20] in terms of the flyway routing and clearance from the new structure. The common finding was that, besides bats flying right over the structure, there are quite a number of them that choose to fly several meters away from it and follow sinusoidal rather than a straight-line path. Bats can sometimes increase their flight height above the structure or follow a sine path when flying next to it, dropping slightly below the floor mesh. Similar observations were made by authors of Reference [18] during their study of spherical structures. While all the above-mentioned studies analyzed the situation with separate consideration of the different bat species and their flight techniques, the issue of how readily the same structures are used by bats at different locations was not addressed and the relevant determinants have not yet been sought. One of the key conclusions of the studies reported in References [19,20] was the negative impact of gaps in the corridor leading the bats to the crossing structure (i.e., lack of gap-filling vegetation). The second major conclusion is the essential need to maintain the existing commuting routes, as confirmed several times by the study results and as described in the conclusions and recommendations of publications [4,6,18].

3. Methods of Monitoring and Parameters of Roads that Affect Movement of Bats

Performance or failure to perform the analyzed bat gantries, installed over the S3 expressway, was assessed on the basis of a few parameters defining impact of the road traffic on the routing and frequenting of the commuting routes by bats. The pre-defined impacts of road parameters should be confirmed by the bat activity survey data and the types of commuting movements of different bat species, which should be determined as part of the basic studies to be conducted by chiropterologists. Three monitoring survey methods were used in the research [11,25–27]. In the first method, the most popular among the three, bat detectors are deployed under each structure. The shortcoming of detector-based surveys is that they indicate solely the space without determining the flight height or direction. The frequencies of ultrasounds are recorded and they are, subsequently, used in computer analysis. The primary purpose of the computer analysis was to acquire information on the bat species commuting in the close vicinity of the analyzed crossing structure. The next method is based on identification and counting of roadkill on the road and on its shoulders in the vicinity of the installed crossing structures. In the third method, bats were observed by a chiropterologist in flight (direct observations). The present article uses monitoring data summarized in References [25–27].

The issue of road features having a potential negative impact on the commuting movements of bats was investigated through review of available chiropterological literature in which the researchers described the types and results of the relevant experiments. The literature review concerning the analysis of linear landscape features guiding bats to the crossing structure covered primarily the results of studies of the negative impacts on the movements of bats, published in References [2,4,14,19,20,29–33], including: road lighting, traffic noise, volume of traffic, or alterations to the linear landscape features. With such a vast area of study, it was necessary to adopt basic assumptions concerning evaluation of the influence of the respective individual features on the performance of the bat gantries under analysis [34,35]. The recommendation for the analytical study is to choose sections having the same or almost the same values of parameters representing the different features except for the feature under analysis represented by parameter x. This approach to experimental research enables estimating the magnitude of influence of the analyzed feature of the road.

According to the conclusions of studies on the negative impact of the volume of traffic on the number of bat flights [4,14], this factor should be considered relevant to evaluation of the bat gantries' performance. Taking this into account, the essential requirement of equal traffic volume at the analyzed locations should be considered satisfied since the gantries under analysis are located on one section of the S3 expressway at ca. 1.2 km intervals.

On the analyzed commuting routes, the linear landscape features have not been altered, except for clearing of trees in the right-of-way belt. Note that clearing width was the same at the three analyzed locations. This also ensures constancy of this parameter. The varying parameters were the landscape features at the respective gantries. The landscape features have a bearing on the illumination of the road surroundings and also on the traffic noise propagation.

The symmetric layout of landscape features along the S3 expressway and along the planned commuting route is ensured only at gantry No. 2 (Figures 5 and 7). At gantry No. 3, which is aligned with the forest edge, the landscape features are symmetric along the S3 expressway only in the summer and autumn (Figures 6 and 7). The big wooded area near gantry No. 3 planted with deciduous trees, that are bare in November and March, does not ensure symmetry of landscape features on the two sides of the constructed road. This lack of symmetry is also the case along the commuting route surrounded by the wooded area on one side and by farm fields on the other. In the case of gantry No. 1, we are dealing with no symmetry, as far as the layout of landscape features is concerned. In addition, part of the area is open and, thus, exposed to light pollution from streetlights of the three-level interchange and from the headlights of cars travelling on it (Figures 4 and 7). Gantry No. 1 is aligned with the forest edge. This means a similar lack of symmetry of landscape features along the commuting route. The three-level interchange is another feature responsible for the lack of symmetry along the S3 expressway. The ramps on the interchange are constructed at grade, in cuts, or on high fills. Additionally, the A6 motorways have varying grade lines, starting from grade level in the western part and dropping to ca. 4–6 m below grade in the eastern part. In the author's opinion, the above-mentioned asymmetric layouts of the landscape features are also relevant to the performance of the constructed gantries.

A significant problem in analyzing the performance of bat gantries is the effect of road lighting and car headlights. The negative impact of road lighting on the movements of bats is broadly described in References [29–31]. For example, the authors of Reference [30] studied the effect of the type of lighting and illumination level on different bat species and how road lighting influences the activity of bats on their established commuting routes. According to the authors, the test data demonstrate that "... light pollution may have significant negative impacts upon the selection of flight routes by bats" [30], (p. 1127). In the summary, the authors formulate a hypothesis that "... light pollution may force bats to use suboptimal flight routes, potentially causes isolation of preferred foraging sites ... " [30], (p. 1127). Therefore, taking into account the above conclusions and recommendations, it appears necessary to consider the effect of light pollution as an obligatory requirement in order to ensure sustainable design of bat gantries, including both selection of the location and the type of structure assisting the bats in crossing the road.

According to the Australian guidelines [31], (p. 90) car lights "... can be visible up to 90 meters into the forest and further in open areas ... " (Figure 9). Scattered light of head-lights and tail-lights of cars travelling across a forest create undesired reflections, disturb all animal species, can scare animals, and even make them abandon their habitats.

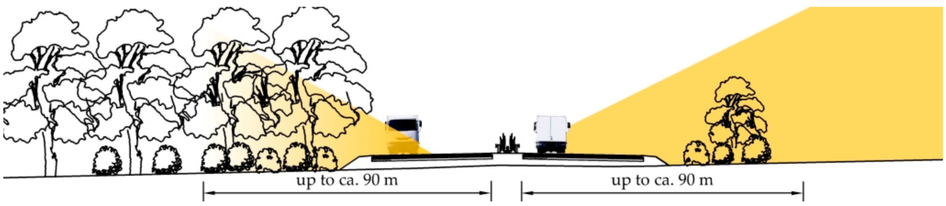


Figure 9. Propagation of light beams of car headlights through a forest and in an open area (pictured on the basis of Reference [31], (p. 91)).

Consequently, sustainable design of roads and the features related to conservation of bat flyways should take into consideration landscape features on both sides of the road in the nearest vicinity of the crossing (including wooded areas, groves, farm fields, and linear features) and appropriate compensational measures (physical) should be planned to considerably mitigate the negative impacts of artificial lighting on wildlife, including installation of screens, earth berms (Figure 10), or lowering of the road grade line below the surrounding area. The areas requiring particular attention in terms of environmental compensation are clearly defined by the environmental conditions. These are nesting sites and waterlogged areas with a likely presence of local habitats, which can be potential foraging areas for bats.

Figure 10. Example of measures to mitigate the negative impacts of headlight beams penetrating the area adjacent to the road: gap-filling vegetation or earth beams (pictured on the basis of Reference [31], (p. 92)).

Environmental compensation can be provided, for example, by screening structures protecting the habitat areas. In the case of bats, such screens additionally lead them to foraging grounds and to the crossing structure as well. This is, however, a costly option and the environmental benefits of it are still under evaluation. The total screen height should be determined depending on the topography of the area with 1.4 meters being the minimum height to effectively block the headlight beams [31]. Higher screens are required where the roads run on slopes and the headlight beams can reach much deeper into the open area. Negative impacts of artificial light can be mitigated by planting gap-filling vegetation near the carriageway or by lining the road with earth beams (Figure 10).

The next parameter of roads that must be considered in designing and erecting features associated with the protection of bat commuting routes is propagation of traffic generated noise into the surrounding area along the road. Higher noise levels can affect auditory perception of predators, which increases the predation rate, and the mating calls of males, which affects breeding success. The aspects of the negative impact of road traffic noise on bats are discussed in References [31–33]. In the conclusions of the experimental research described in Reference [32], the authors point out that, in a sustainable design of motorways, it is necessary to take into account potential foraging sites and winter roosts rather than only the commuting routes of bats. From the research data, it can be seen that a high level of traffic noise makes the bats discard any foraging areas within the strip of 10 to 15 meters from the road. In addition, foraging sites spaced 50 meters away from the motorway were not accepted by bats due to a high level of traffic during the night [32].

According to the previously mentioned conclusions, the existing roosts of bats and location of crossing structures to be provided on their commuting routes should be analyzed in terms of the traffic noise level. It is worth mentioning that vegetation, whether natural or artificial (planted in gaps), is a "soft" kind of noise mitigation measures. The plantings to fill the gaps should always match the existing vegetation. Deciduous trees and shrubs are more effective in attenuating noise, as compared to coniferous trees. Yet, the latter are useful as a supplementary measure in the periods when the former are devoid of leaves [31]. Hence, the gap bridging vegetation near the planned structures assisting bats in making their way across the road should include both coniferous and deciduous plants. The Australian guidelines [31] depict the negative impact of the sound wave propagation similar to the impact of artificial light presented in Figure 8. The existing forests and artificial vegetation in the form of small groves were composed of a few rows of plants at the forest edge along the constructed road, which reduce the noise level considerably while, on the other hand, individual trees growing along the road have no significant effect on noise reduction in their vicinity. The sound wave propagation is considerably disturbed (meaning much greater noise reduction) when the sound wave meets on its way vegetation composed of plants of different heights and varied species composition. The author's own studies demonstrate that the greater the variation of vegetation, including both height and species' composition, the better the noise reducing performance of this mitigation measure [36]. Moreover, the noise reducing effect can be considerably improved when two or three rows of tall tree species are supplemented with shrubs in the undergrowth level.

Lowering the grade line below the surrounding area or lining the road with earth berms in flat areas can also do the job. However, the cost of such measures is high. For example, earth berms must be sufficiently high to be effective and this height translates to greater footprints and increased cost of a land purchase.

The negative impacts of road lighting and traffic noise can be mitigated on bat commuting routes by natural type structures, such as hop-overs. The design originally proposed by the Dutch researchers in 1991 [29], have been since then supplemented in many aspects by different guidance documents published in the Netherlands and in other countries [4,6,7]. Coming to the end of this part of the article, which concerns assessment of road characteristics in terms of their effect on noise reduction, it is worth noting that there are on-going research projects related to the application of pavement surfaces attenuating traffic noise and various types of quiet tires that can result in the reduction of road traffic noise. However, these new developments are still in the experimental stage, have not yet been completed, and, in the analyzed case, are only secondarily related to bat crossings' performance.

Following presentation of the methods and road characteristics that can adversely impact the crossing movements of bats, the further part of this article will analyze the effect of light pollution, noise, and artificial gap-filling vegetation at the installed gantries on their performance at three different locations, which correlates them with the reported monitoring survey results [26,27].

4. Results

4.1. Analysis of the Effect of Road Lighting Pollution on Bat Gantries' Performance

Considering the above facts, in analyzing the performance of gantries built over the S3 expressway, the author paid particular attention to symmetric or non-symmetric layout of land features about the axis of the road section in the Puszcza Bukowa forest area. The conditions related to the commuting of bats before construction of the S3 expressway are presented in Figure 11. At that time, the impact of the road lighting was noted only along the existing A6 motorway, especially on its western part, which runs in the open area. The eastern part of A6 runs in a road cut, surrounded by an area with randomly distributed patches of vegetation, which scatters the headlight beams.

Figure 11. The impact of artificial lighting on the bat commuting routes in the Puszcza Bukowa forest before S3 construction (plotted on a Google Earth satellite image from 2004) [28]).

Analyzing the lighting pollution situation along the constructed S3 expressway in two seasons of the year, namely in spring (Figure 12) and in summer (Figure 13), it can be concluded that the area that is the most exposed to light pollution is in the vicinity of gantry No. 1. This is due to the asymmetric layout of landscape features, taking the S3 expressway as the axis of symmetry, and along the bat flyway. At gantry No. 1, the expressway is level with the surrounding area ("at grade" section). The gantry No. 3, in turn, spans the road section constructed in a 3-meter deep cut, with symmetric slopes protecting the surrounding area from light pollution by strong headlight beams (Figures 12 and 13). The negative impact of scattered light is more severe in the part of the forest with deciduous trees, in particular, in March (Figure 12). On the other hand, the conditions are the most favorable and the negative impacts of the road are the smallest around gantry No. 2. At gantry No. 2, the road runs in cutting. In this case, 2 meters deep and the same as previously, the symmetric slopes provide partial protection of the surrounding area from light pollution by strong headlight beams. In addition, light does not deter bats due to the symmetric and wide forest opening with few tall trees growing in its area. The medium tall trees and shrubs provide effective protection of the bat flyway area.

This situation is still improved by additional plantings on both sides of gantry No. 2, which provide protection of the approach section and encourage bats to raise their flight height when passing over the road.

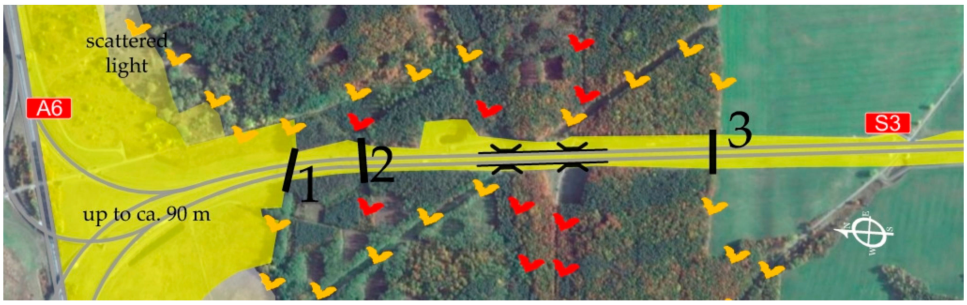


Figure 12. The impact of artificial lighting on the bat commuting routes in the Puszcza Bukowa forest after S3 construction, in March (plotted on a Google Earth satellite image) [28]).

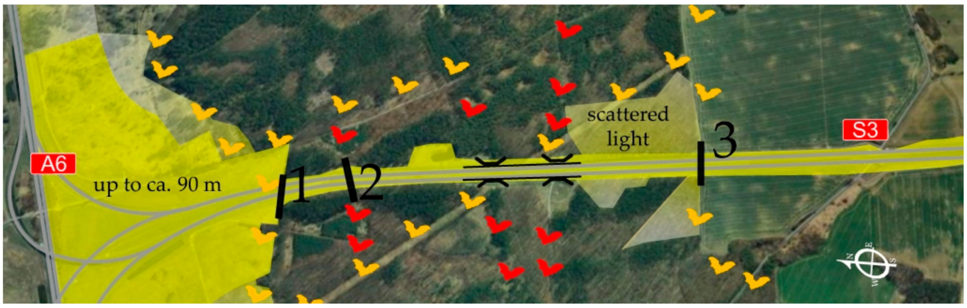


Figure 13. The impact of artificial lighting on the bat commuting routes in the Puszcza Bukowa forest after construction of the S3, in summer (plotted on a Google Earth satellite image) [28]).

More details concerning light pollution from road lighting and headlights in the close vicinity of gantry structures are given in the detailed layout plan and in the cross-section drawings in Figures 14–16. The area right at gantries No. 1 and No. 2 is additionally lit by typical road lamps of the nearby three-level interchange. The distance to the nearest lamps is the smallest in the case of gantry No. 1. During the monitoring survey, foraging activity of certain bat species was observed near this structure. This was caused by the presence of *Eptesicus serotinus*, *Nyctalus noctula*, and *Nyctalus leisleri*, i.e., insects which are their primary food, attracted to the space above the road surface lit by the road lamps [26]. The surrounding open area and the pavement surface are additionally lit by the headlights of cars travelling on exit ramps. This situation discourages all the bat species that used to commute on this route mainly because of a very illuminated area to the north of gantry No. 1.

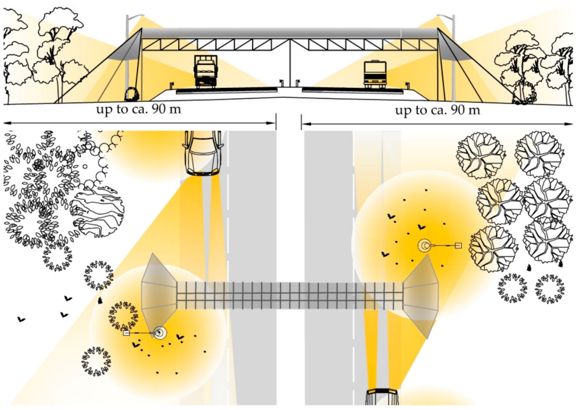


Figure 14. Visualization of light pollution in the vicinity of gantry No. 1 (at grade section of the road).

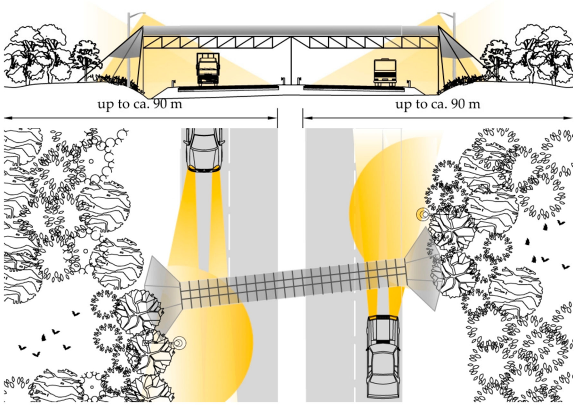


Figure 15. Visualization of light pollution in the vicinity of gantry No. 2 (road in an up to 2-meter deep cut).

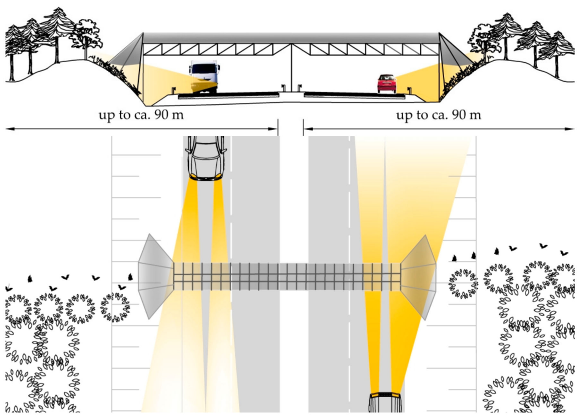


Figure 16. Visualization of light pollution in the vicinity of gantry No. 3 (road in a ca. 3-meter deep cut).

Analyzing the light pollution situation presented in Figures 12–16, we note the relevance of landscape features on both sides of the road and on both sides of the structure as well. The layout of landscape features is symmetric about the road and commuting route centerlines only in the case of gantry No. 2 located in the forest opening (Figure 15). In the analyzed case, it has been determined, based on the survey data, that, in the period 2010 to 2012, the primary function of this measure was to support bat movements [26,27]. In line with the conclusions of References [19–21,30], we can state that the following tree cutting in relation to the road construction works, which severed the existing linear landscape features used by bats for commuting, they started searching for a new route, which leads to their winter roosts and, finally, chose the route with gantry No. 2 on the way. Additionally, they also use the old part of the route along the forest opening edge, where two underpasses have been constructed in the course of the existing forest tracks. Both gantry No. 2 and the wildlife underpasses are surrounded by symmetric landscape features, and this symmetry is ensured about the centerlines of both the road and the commuting route. This is important since the existing trees are very effective in limiting penetration of light into the area, i.e., the negative impact of the road on bat movements. At the underpasses, there are screens installed along the road, which protect the adjacent areas from light pollution. The observations and site visits in the area of gantry No. 2 carried out by the author in different months confirm favorable environmental conditions, which are not compromised by road lighting. This is due to naturally growing trees and additional gap-filling vegetation.

In the case of asymmetric layout of land features about the axes of the commuting route and the S3 expressway, it appears that only gantry No. 3 becomes gradually accepted by bats, as confirmed by the results of 2010 to 2012 bat activity surveys (Figure 8) and, as such, it can be more effective in the future, which is the same as gantry No. 2. It is reached by headlight beams only for a moment when a car is passing under it. With the open area surrounding the road in advance of the structure and morning fogs, which take over this area in March and effectively disperse the headlight beams, the bat movements are not disturbed there. During successive observations of lighting conditions in different months of the year, no flickering of reflected headlight beams was noted on the metal parts of the structure. The bat activity survey data [26,27] show that the route was used by bats not only for migration but also for commuting to the nearby foraging sites (fields and habitats).

On the other hand, in the case of gantry No. 1, located in an open area in close vicinity of the three-level road interchange and aligned with the forest edge (Figure 17), we have no grounds to confirm acceptance of the route by bats or the effectiveness of the chosen gantry structure design. The three-year long studies and comparison of the flight counts on the same days and times indicate that this route, rather than for commuting, will be used by certain bat species as the foraging site and this is only from time to time. The probable primary cause of this poor performance of gantry No. 1 is the light pollution of the area adjacent to the forest by the lighting of a three-level interchange and by headlights of cars travelling on the interchange exit ramps, which disturb the bats during flights. This hypothesis is based on the analysis of the lighting conditions presented in Figures 11–13 and Figure 16 and of the conclusions of Reference [30].

Figure 17. Artificial lighting during the night near gantry No. 1 [37].

4.2. Analysis of the Effect of Artificial Vegetation on the Bat Gantries Performance

Taking into account the height of gantries and their distance from the forest edge, the landscape engineer proposed to use in the guiding corridor small leaved lime-trees (*Tilia cordata*), arranged in a V pattern, four per leg, spaced at 5-meter intervals [38,39]. This tree species was chosen because of an easily-shaped crown and fast growing nature. It was planned that, after a few years, when the trees have sufficiently developed, they would be adjusted in height. This would have been a challenging or even impracticable task in the case of other tree species. Another factor supporting selection of the small leaved lime-tree was its resistance to pollution generated by road traffic. Moreover, the lime-trees were expected to overtop the structure in a few years, which, more effectively, encourages the bats to increase their flight height over the installed structures. The following shrub species were planted in the gaps between the tree trunks to seal the corridor: common barberry (*Berberis vulgaris*), bloody dogwood (*Cornus sanguinea*), European dewberry (*Rubus caesius*), alder buckthorn (*Frangula alnus*), blackthorn (*Prunus spinosa*), and warty-barked spindle (*Euonymus verrucosus*).

The V-shaped vegetation corridors were actually planted only at gantry No. 2 in 2010. The plants have established themselves and have overtopped the structure by now (Figure 18). However, the gaps between the lime-trees were not filled by shrubs. Instead, considering the local conditions, various shrubs and trees were planted in thinly vegetated parts of forest openings in order to seal the corridor and make bats increase their flight height (Figure 19). This crossing was the most problematic one because bats flew between pine trees dropping onto the road right in front of the cars. This called for sealing the gaps between the naturally growing trees with fast growing tree species, as shown in Figure 5.

(**a**) (**b**)

Figure 18. Plantings at gantry No. 2: (**a**) guiding and gap-filling vegetation in the forest opening area to the east of the S3 expressway, and (**b**) guiding vegetation to the west of the S3 expressway.

Figure 19. Gap-filling vegetation, planted to seal the gaps in thinly wooded, wide forest opening, and encourage bats to increase their flight height at gantry No. 2.

Effectiveness of gantry No. 2 is confirmed by the results of the 2010 to 2012 bat activity surveys, as presented in Figure 8. Filling and guiding vegetation has most likely contributed to this success. The trees and shrubs grew year by year and overtopped the gantry structure in 2019 (Figures 18b and 19). The artificial vegetation planted to seal the gaps in forest openings on both sides of the expressway has also contributed to rising the height of the flight of bats on the approach to gantry No. 2 (Figure 18a) and, together with the slopes of a 2-meter deep cut, considerably mitigated the negative impacts of light and noise pollution. In the analyzed case, light from the nearby road lamps will not attract insects, which would make bats stop in order to forage or would disturb their flight (Figures 15 and 20).

Figure 20. Artificial lighting during the night near gantry No. 2.

At gantry No. 1, the V-shaped vegetation corridor was actually planted only to the east of the road (Figure 21). However, the plants have established themselves poorly (Figure 21b) and, after nine years, they fulfill neither orientation nor a guiding role. To the west of the road, four lime-trees were planted in line with the forest edge (Figure 21a), which, however, did not grow as expected after nine years. This reached only half way up the structure height. Additionally, these plants do not serve the orientation or guiding purposes. The performance of gantry No. 1 is further compromised by the asymmetric arrangement of landscape features (Figures 21 and 22) due to the open area at this location. With a lack of well-developed guiding vegetation, gaps in the approach corridor and open area, which does not mitigate the negative impacts of traffic noise and light pollution from the interchange lamps (Figure 17) and headlight beams, the conditions cannot be considered favorable for successful performance of gantry No. 1.

(**a**)

(**b**)

Figure 21. Plantings at gantry No. 1: (**a**) guiding bats from the area to the west of the S3 expressway and (**b**) guiding bats from the area to the east of the S3 expressway.

Figure 22. Landscape features and thin groves at gantry No. 1.

In addition, at gantry No. 3, a row of four trees were planted in line with the forest edge (Figure 23). On the western side, the trees have developed well and are almost as high as the structure. The plants on the eastern side are set back from the structure and forest edge lines by ca. 2 m. Only three trees have developed and are currently ca. 5 m tall. Moreover, on the eastern side of the road, the forest edge is closer to the structure due to the service road location (Figure 23b). With no light pollution from the road lamps, ca. 3-meter deep road cut, artificial vegetation, and keeping the pre-construction commuting route make this location very favorable to support bat movements. In addition, the farm fields located near the road make a foraging area for bats. It is likely the combined effect of the above-mentioned factors that resulted in increasing numbers of bat passes observed during bat activity surveys (Figure 8).

(a) (b)

Figure 23. Plantings at gantry No. 3: (**a**) guiding bats from the area to the west of the S3 expressway and (**b**) poorly developed vegetation designed to guide bats from the area to the east of the S3 expressway.

4.3. Analysis of the Effect of Traffic Noise on the Bat Gantries' Performance

Mitigation of the traffic noise is one of the key steps on the way to ensure favorable commuting conditions for bats, which is a prerequisite for successful performance of the installed bat gantries. Considering the conclusions published in Reference [32], the author measured road traffic noise on the bat flyways near the installed gantries and plotted the relevant noise maps. The baseline noise map illustrates the noise distribution pattern around the A6 motorway only, i.e., before construction of the S3 expressway and gives the traffic noise levels on the established bat flyways (Figure 24). In the analyzed case, the author used the daily traffic level counts of the general traffic surveys in 2000 and 2005, calculating the hourly traffic level during nighttime in the summer. In developing the noise map showing the situation before construction of the S3 expressway, the author placed the observation points along the bat flyways at 6 meters in height, by considering the subsequent comparison of the noise levels in the course of the flyway over the installed bat gantries. The analysis of noise distribution illustrated in the noise map showed that, before construction of the S3 expressway, the noise level at the flight height of bats 6 meters above the ground ranged from 40 to 50 dB (A), except for the route running closest to the motorway where it ranged from 50 to 55 dB (A).

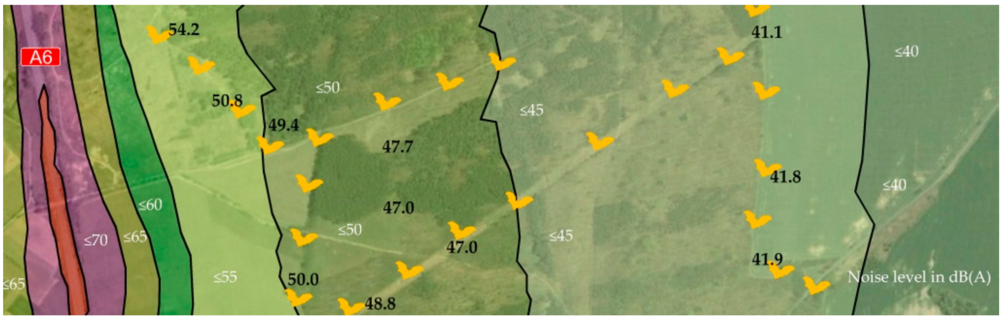


Figure 24. Noise map and noise levels on the bat commuting routes before construction of the S3 expressway (plotted on a Google Earth satellite image from 2004) [28]).

The noise distribution presented in Figure 24 shows that the most favorable sound environment to support bat movements, with noise levels in the range of 41–42 dB (A) is on the route where gantry No. 3 was subsequently installed. At the future location of gantry No. 2, the level of noise ranged from 47 to 48 dB (A). The forest edge located closest to the A6 motorway, i.e., at the future location of gantry No. 1, the level of noise of 50 dB (A) was recorded. Considering the bat commuting routes before construction of the S3 expressway, we can state that the sound environment was favorable to bats on their existing routes.

There are several publications [1,4,6,7,19,20] in which the authors conclude that, in order to make bats keep using their established routes after construction of a new road, it is necessary to ensure equivalent conditions thereon. Thus, it was necessary to analyze the levels generated by the road traffic on the established commuting routes after S3 expressway construction. To this end, night-time traffic volumes were calculated for the A6 motorway, S3 expressway, and interchanging ramps in relation to the conditions of the 2010–2012 bat activity surveys. The traffic volumes during the busiest night hours in March and in the summer were adopted for the calculations. The 2015 general traffic survey data were used as calculation input. On this basis, the traffic volumes from 2010 to 2012 were calculated.

The analysis of the existing situation covered the 2.5-meter high screens installed at wildlife underpasses, and actually highly variable landscape features. The vegetation development conditions in the Puszcza Bukowa forest were compared in two characteristic periods of the year, i.e., in spring—when deciduous trees are bare and living pine trees have green, developed parts of crown starting from 6 meters above ground and reaching up to 12 meters and in the summer—when gaps between the pine trees are sealed by smaller deciduous trees and shrubs accompanied by up to 6 meters and up to 10-meter tall deciduous trees. Seasonal variations were taken into account for the farm fields, i.e., low vegetation in spring, reaching up to 1-meter in summer (in the case of cereals). Grass cover of land was assumed for forest clearings and road cut slopes. As the next step, the original grade levels were recovered, together with the A6 and S3 grade lines (to the extent under analysis), by differentiating between sections constructed at grade, in cutting or on fill. Taking into account the above conditions, the noise map was prepared for the area around the S3 expressway and the three installed bat gantries, separately for spring and for winter representing the noise levels at the flight heights of bats, i.e., over the crossing structures. The noise map for summer is presented in Figure 25.

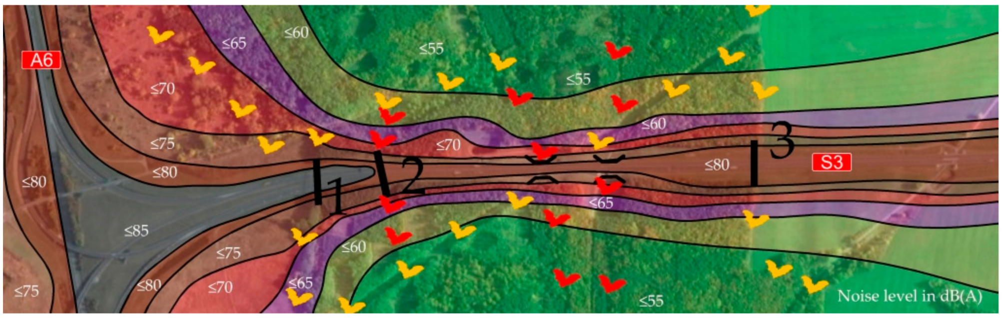


Figure 25. Noise map and established bat commuting routes in the summer (plotted on a Google Earth satellite image) [28]).

The most favorable commuting conditions were noted on the route leading to gantry No. 2 located at a wide forest opening with the shortest of all sections with noise level in excess of 60 dB (A). The route in the forest opening related to the overhead power line right-of-way was rated as the second most favorable one, with noise levels below 55 dB (A). The two 2.5-meter high screens installed at the underpasses on the S3 expressway route reduced the noise level along the forest tracks to as low as 40 to 45 dB (A). The noise map in Figure 25 represents the estimated noise levels at 6 meters height above the ground. In the forest opening and under the two underpasses, bats fly at lower heights where the noise levels are much lower as compared to the 6-meter height over the S3 expressway. The noise levels given in the noise maps in Figure 25 were calculated for the monitoring stations located 6 meters above the ground. Worse flight conditions were noted at structures No. 1 and No. 3 with noise levels of 80 to 85 dB (A) or 75 to 80 dB (A) persisting over much longer sections.

For the purpose of analyzing the noise distribution in the area under analysis, more than one dozen monitoring stations were deployed on the established commuting routes at 6-meter and 8-meter heights along the installed crossing structures. The output noise data are presented in the comparative diagrams below (Figures 26 and 27).

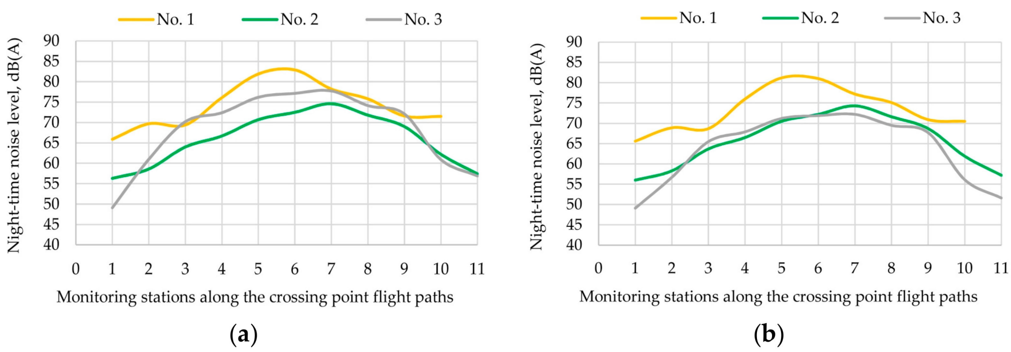


Figure 26. Comparison of the noise levels on the bat commuting routes over the installed crossing structures in spring: (**a**) at 6-meters above the ground and (**b**) at 8-meters above the ground.

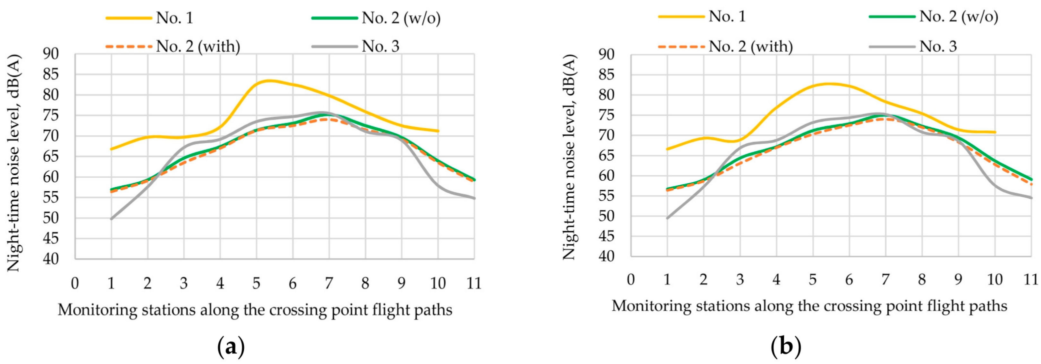


Figure 27. Comparison of the noise levels on the bat commuting routes over the installed crossing structures in summer: (**a**) at 6-meters above the ground and (**b**) at 8-meters above the ground.

According to the spring survey data, the most favorable conditions for bat movements are over gantry No. 2 at both heights and over gantry No. 3 at 8-meters in height. This is a likely cause of the highest number of passes recorded in the spring over gantry No. 3, which is located on the pre-construction route, in a place without any road lamps in the vicinity and with the surrounding fields used by bats as a foraging site. Considering the conclusions of the relevant studies [19,20], we can propose a hypothesis that, after noticing adverse changes on their established commuting routes, the bats switched to the route in the forest opening and through the underpasses and tested the new route along gantry No. 2. The results in favor of this hypothesis are the increasing numbers of passes over gantry No. 2 in the subsequent years of monitoring (Figure 8). The high noise level over gantry No. 1, illumination of the nearby interchange, penetration of headlight beams into the surrounding area (particularly disadvantageous in the case of cars travelling on the highest-level exit ramp), and the lack of mitigating vegetation created the most unfavorable conditions, which deterred the bats from using their established route. It is likely the combined effect of all the above-mentioned factors that discouraged bats from using this route regularly (Figure 8), which results in poor performance of gantry No. 1.

Similar conclusions can be derived in relation to the summer survey data (Figure 27). For the purpose of the current analysis, the noise levels were additionally estimated for the situation after planting of filling and guiding vegetation in the wide forest opening on both sides of the S3 expressway and on both sides of the flyway over gantry No. 2 (broken line in Figure 27). Moreover, the results show that additional plantings to seal the forest opening area and encourage bats to increase their flight height and guiding vegetation leading the bats over gantry No. 2 reduced the noise level on the bat flyway by 0.5–1 dB (see comparison in Figure 27. No. 2 (w/o)—solid line, representing noise levels without additional or guiding vegetation in the forest opening, No. 2 (with—broken line, representing noise levels with the additional and filling vegetation already in place). According to the noise data, the most favorable conditions for bat movements are over gantries No. 2 and No. 3 with the maximum recorded noise levels not exceeding 75 dB (A). On the other hand, noise levels in excess of 80 dB (A) was recorded over gantry No. 1, right over the carriageway (monitoring stations No. 5–7).

Based on monitoring surveys carried out for several years, the author confirmed only that, over the period from March to May, the greatest bat activity was noted in the surroundings of gantry No. 3 while, in the entire research period from mid-March to mid-November, their greatest activity was noted at gantry No. 2, in the vicinity of a wide forest opening and a thinned forest (Figure 8). The lowest intensity of bat activity was noted at gantry No. 1 at km 0 + 660 due to the presence of road lamps at both sides of the road and due to the noise levels in excess of 80 dB (A) [26,27].

5. Discussion and Conclusions

Analyzing the above data, a hypothesis can be put forward that the existing lighting of the expressway, noise, location of the structure in relation to the three-level interchange, landscape features along the bat commuting route, and location of the structure in relation to the forest were the factors that might have had an important effect on the effectiveness of the installed structures. The results of the analysis of an impact of a given factor on the gantry structure performance presented in chapter 5 are compiled in Table 1, where, if the impact of a given factor was negative, the factor received a minus (−) while, if the impact was positive, the factor received a plus (+).

Table 1. Compilation of the results of the effect of an analyzed factor on the effectiveness of the gantry structure.

Analyzed Factor	Gantry No. 1	Gantry No. 2	Gantry No. 3
General factors:			
Road lighting system	−	+	None
Lighting by headlight beams [1]	−	+	+
Interchange in a close vicinity	− [2]	No interchange	No interchange
Traffic noise	−	+	+
Undesirable foraging areas over the carriageway under road lamps	−	+	No lighting
Convenient foraging areas in the vicinity	−	None	+
Location on the established commuting route	+	+ [3]	+
Symmetrical layout of landscape features on both sides of the road	−	+	+
Analyzed determinants:			
Road constructed in a cutting	−	+	+
Approach route in a forest opening	−	+	−
Symmetrical layout landscape features on both sides of the commuting route	−	+	−
Symmetrical guiding vegetation of appropriate height	−	+	−
Filling vegetation on the approach route to the structure	−	+	−
Bat friendly approach route to the crossing structure [4]	−	+	+

[1] Illumination of the road surroundings with the headlights of the vehicles travelling down the road. [2] Structure No. 1 is located in the vicinity of the interchange, which is an adverse factor. [3] The commuting route at gantry No. 2 became established over the period of road construction from 2008 to 2010. [4] No adverse impacts from noise and lighting occur along the approach section of the route.

A comparative analysis of the investigated factors that could potentially have an effect on the effectiveness of a gantry structure revealed that they could be subdivided into general factors and the main determinants of the expected good performance of the gantry structures were used (Figure 28). When designing a road and planning locations of structures intended to assist bats in making their way across the road, if general conditions are met as a prerequisite, in order to achieve good effectiveness of a gantry structure, it is necessary to ensure that other relevant factors, being the main determinants, are satisfied.

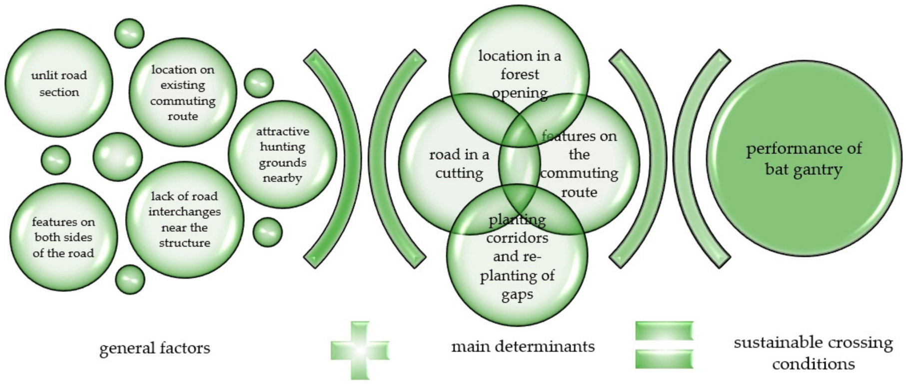


Figure 28. General factors and main determinants have an effect on the effectiveness of the used bat gantry structures.

This means the necessity to analyze the existing bat commuting routes and plan the location of the crossing structure in the forest opening and over the planned road, placed in a cutting over this section, and take every effort to provide suitable improvements along the approach route to the structure in the form of symmetrical guiding vegetation plantings or, if need be, filling vegetation in forest openings. This will encourage bats to increase the flight height and will protect them from the noise and light pollution.

If the existing commuting route does not lead through the forest opening but along the forest edge, it will also be beneficial to design the road in a cutting and provide suitable landscape features comprising guiding and filling vegetation. As for the filling vegetation, it can be provided in the forest area in the immediate vicinity of the road and possibly in the green belts along the cutting edge. If the existing bat foraging areas are located in the immediate vicinity of the structure, filling vegetation should be designed along the approach routes.

The analyses show that the more symmetrical is the layout of the surrounding landscape features in relation to the road and to the commuting route, the more protection from noise and light pollution they offer to the bat gantry, which improves its performance. The results of analyses regarding maintaining the symmetrical landscape features when designing structures to support bats in crossing the roads can be used in different countries for structures other than those investigated in this article.

The results of analyses of bat gantry area illumination show that the closer the edge of the forest is situated to the gantry structure and the more symmetrical are the landscape features, the less is the approach section affected by the headlight beams and noise. The situation is similar with noise propagation. The more artificial vegetation is present in the nearest vicinity of the crossing structure on both sides of the road and of the flyway, the greater is the noise reduction on the bat flyway. Vegetation planted symmetrically on both sides of the road to fill gaps in the forest openings makes the bats increase the height of flight and restricts access of light and noise to the approach route and to the place where bats rise in altitude to fly over the structure, which encourages the bats to use the route. On the other hand, aligning the crossing structures with the forest edge, with an asymmetrical landscape feature on both sides of the flight route, does not guarantee the desired performance of the structure. Several other conditions need to be met in this case so that the structure is accepted by bats. Conversely, without such a symmetry along the approach section, the structure may fail to perform.

If installation of a bat gantry is planned where the road intersects a forest opening, then a special lamp covers restricting propagation of light into the shoulder and the adjacent area should be specified for the road section in the nearest vicinity of the location. The light emitted by road lamps should illuminate only the surface of the road. If there is a fencing along the edge of the road, filling vegetation should be plated over the length of trapezoidal guiding corridors to fill the gaps between the guiding plantings, which, in this way, restricts the access of light emitted by road lamps. Elderberry (*Sambucus nigra*) and violet willow (*Salix daphnoides*) can be used for this purpose, which are fast growing species with good screening properties. In addition, they feature high resistance to traffic pollution.

Bat gantries should not be located where road elements with a potential to have an adverse impact on the commuting route are planned to be installed on or are at the route, including road lighting elements associated with interchanges or service areas, as this will compromise their performance below an acceptable level.

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References

1. Lesiński, G. *The Effect of Anthropogenic Landscapes Transformations on the Structure and Functioning of Bat Communities in Poland*; SGGW Publishing House: Warsaw, Poland, 2006.
2. Ministry of Agriculture, Food and the Environment. *Documents for the Mitigation of Habitat Fragmentation Caused by Transport Infrastructure: Technical Prescriptions for Wildlife Crossing and Fence Design*, 2nd ed.; Ministry of Agriculture, Food and the Environment: Madrid, Spain, 2016.
3. Kelleher, C.; Marnell, F. *Bat Mitigation Guidelines for Ireland*; Marnell, F., Ed.; Department of the Environment, Heritage and Local Government: Dublin, Ireland, 2006.
4. Limpens, H.J.G.A.; Twisk, P.; Veenbaas, G. *Bats and Road Construction*; Rijkswaterstaat, Dienst Weg-en Waterbouwkunde (DWW): Delft, The Netherlands, 2005.
5. Hinde, D. Nature Conservation Advice in Relation to Bats. Interim Advice Note IAN 116/08. Available online: http://www.standardsforhighways.co.uk/ha/standards/ians/pdfs/ian116.pdf (accessed on 28 March 2018).
6. *Information Notes—Economics Environment Design Serie №91*; Sétra: Bats and Road Transport Infrastructure—Threats and Preservation Measures: Lyon, France, 2009.
7. *Routes et Chiroptères—État des Connaissances—Rapport Bibliographique*; Sétra: Lyon, France, 2008.
8. Highways Agency Halcrow Group Limited. *Best Practice in Enhancement of Highway Design for Bats*; Highways Agency Halcrow Group Limited: London, UK, 2006.
9. Abbott, I.M.; Butler, F.; Harrison, S. When flyways meet highways—The relative permeability of different motorway crossing sites to functionally diverse bat species. *Sci. Direct Landsc. Urb. Plan.* **2012**, *106*, 293–302. [CrossRef]
10. Dylewski, Ł. Pollination of plants by animals. *Wszechświat* **2014**, *115*, 128–133.
11. Sołowczuk, A. (Ed.) *S3 Expressway, Section between Szczecin and Gorzów Wielkopolski in Poland*; Comgraph Anna Jadczuk: Szczecin, Poland, 2010.
12. CEDR Transnational Road Research: Roads and Wildlife. *Richtlijnen Voor het Mitigeren en Compenseren van Effecten van Wegen op Vleermuizen*; CEDR Transnational Road Research, Roads and Wildlife: Copenhagen, Denmark, 2016.
13. CEDR Transnational Road Research. *Guía para Mitigar los Atropellos de Murciélagos*; CEDR Transnational Road Research: Roads and Wildlife: Copenhagen, Denmark, 2016.
14. Zurcher, A.A.; Sparks, D.W.; Bennett, V.J. Why the bat did not cross the road? *Acta Chiropterolog.* **2010**, *12*, 337–340. [CrossRef]
15. Wray, S.; Reason, P.; Wells, D.; Cresswell, W.; Walker, H. Design, installation, and monitoring of safe crossing points for bats on a new highway scheme in Wales. In *Wildlife Crossing Structures: Planning, Placement, Monitoring—Chapter 9*; Road Ecology Center, University of California: Davis, CA, USA, 2005; pp. 367–379.
16. National Roads Authority. *Best Practice Guidelines for the Conservation of Bats in the Planning of National Road Schemes*; Livret Technique, National Roads Authority: Dublin, Ireland, 2005; p. 48.
17. Riou, D. Autoroute A89 Chiroptéroduc. Available online: http://www.denisriou.com/autoroute-a89-chiropteroduc (accessed on 28 July 2018).
18. Naturalia Environnement & FRAPNA. *Suivi des Ouvrages de l'A89: Le Cas des Chiroptères, Autoroute A89 Section Balbigny—Violay*; Rapport de Synthèse pour le compte d'ASF, Naturalia Environnement & FRAPNA: Avignon, France, 2015.
19. Berthinussen, A.; Altringham, J. Do bat gantries and underpasses help bats cross roads safely? *J. PLoS* **2012**. [CrossRef] [PubMed]

20. Berthinussen, A.; Altringham, J. The effect of a major road on bat activity and diversity. *J. Appl. Ecol.* **2012**, *49*, 82–89. [CrossRef]
21. Berthinussen, A.; Altringham, J. Bat bridges don't work. 2012. Available online: https://www.sciencedaily.com/releases/2012/06/120613184009.htm (accessed on 7 October 2017).
22. Highways Agency. *Post Opening Project Evaluation A38 Dobwalls Bypass One Year After Study: A38 Dobwalls Bypass One Year after Report*; Highways Agency: London, UK, 2011.
23. Mägerle, G. Fledermäuse nutzen die Brücken, Schwäbische. Available online: http://www.biberach.de/aktuelles/presse/pressearchiv2014/pressemitteilungen-2014-detailansicht/article/fledermaeuse-nutzen-die-bruecken.html (accessed on 22 November 2017).
24. Trautner, J. Videobeweis: Fledermäuse Nutzen die Brücken. Available online: http://www.schwaebische.de/region_artikel,-Videobeweis-Fledermaeuse-nutzen-die-Bruecken-_arid,10054155_toid,112.html (accessed on 12 November 2017).
25. EKKOM. *Environmental Impact Assessment of the S3 Expressway Construction on Natura 2000 Sites, Section Szczecin—Gorzów Wielkopolski (between Interchange Klucz at km 0+000 and Interchange Gorzów North (Excusive of the Interchange Itself) at km 81+613)*; EKKOM: Warsaw, Poland, 2010.
26. Mopek Bat Conservation Association. *Final Report from the 2010–2011 Bat Activity Surveys: Monitoring of Bat Activity along the S3 Expressway between Interchange Klucz (km 0+000) and Interchange Gorzów North (km 81+613)*; Mopek Bat Conservation Association: Szczecin, Poland, 2011.
27. Siuda, P.; Mrugowski, W. *Final Report from Bat Activity Monitoring Along the S3 Expressway, Section between Interchange Klucz (km 0+000) and Interchange Gorzów North (km 81+613)*; Doradztwo Ekologiczne: Szczecin, Poland, 2012.
28. Google Earth. 2019. Available online: http://www.earth.google.com. (accessed on 19 May 2019).
29. Limpens, H.J.G.A.; Kapteyn, K. Bats, their behaviour and linear landscape elements. *Myotis* **1991**, *29*, 39–48.
30. Stone, E.L.; Jones, G.; Harris, S. Street lighting disturbs commuting bats. *J. Curr. Biol.* **2009**, *19*, 1123–1127. [CrossRef] [PubMed]
31. *Technical Publications: Fauna Sensitive Road Design*; Chapter 6; Department of Transport and Main Roads: Fortitude Valley, QLD, Australia, 2011; Volume 2. Available online: https://www.tmr.qld.gov.au/business-industry/Technical-standards-publications/Fauna-Sensitive-Road-Design-Volume-2.aspx (accessed on 12 November 2017).
32. Schaub, A.; Ostwald, J.; Siemers, B.M. Foraging bats avoid noise. *J. Exp. Biol.* **2008**, *211*, 3174–3180. [CrossRef] [PubMed]
33. Reijnen, M.J.S.M.; Veenbaas, G.; Foppen, R.P.B. *Predicting the Effects of Motorway Traffic on Breeding Bird Populations, Road and Hydraulic Engineering Division*; DLO Institute for Forestry and Nature Research: Delft, The Netherlands, 1995.
34. Ivobotienko, B.A.; Il'inskij, B.A.; Kopylov, J.P. *Planirovanie Eksperimenta*; Ehnergija: Moskva, Russia, 1975.
35. Sobczyńska, D. *Mastery of Experimental Studies*; Publishing House of the Adam Mickiewicz University of Poznań: Poznań, Poland, 1993.
36. Sołowczuk, A. *The Impact of Land Development on the Distribution of Road Noise Level on the Surface of the Upper Wildlife Crossings*; LAP LAMBERT Academic Publishing: Berlin, Germany, 2018.
37. Sołowczuk, A. Section Green Design & Sustainable Architecture. In Proceedings of the 18th International Multidisciplinary Scientific GeoConference SGEM 2018, Vienna, Austria, 30 June–8 July 2017.
38. *Detailed Design of Steel Structure of Bat Gantries Over the S3 Expressway between Szczecin and Gorzów Wielkopolski*; VALDI Structural Engineers: Zielona Góra, Poland, 2010.
39. Cichocki, J.; Łupicki, D.; Maciantowicz, M. *Conceptual Design of Bat Gantries Over S3 Expressway*; General Directorate of National Roads and Motorways Branch in Szczecin: Szczecin, Poland, 2010.