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Identification of the Key Determinants of Bats' Altitude Increase over the S3 Expressway in Poland with Mesh Screens Applied

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Abstract: The continuing increase in motorisation and the resulting development of the road infrastructure puts increasing demands on environmental protection, and on the protection of bats in particular. One of the available mitigation measures is mesh screen structures installed on dual carriageways. However, not all the mitigating measures turn out to be effective and functional. Mesh screens were installed along a road section over a dozen kilometres long near a large bat reserve in Poland (40,000 bats). As part of post-construction work, bat mortality monitoring was conducted over a 3–4 year period in order to assess the effectiveness of the mesh screens in raising the height of bat flyways. An analysis of the mortality surveys and the locations of bat carcasses found along the expressway allowed the authors to confirm that the screens may contribute to raising the height of bat flyways, yet this effect should be considered in combination with other determinants identified during the surveys. The article presents the main determinants, which together with the mesh screens installed along a dual carriageway road over the length of several kilometres, can contribute to the effective raising of the height at which bats fly across the road. The most important determinants included: retaining the continuity of linear landscape features along the confirmed bat commuting and migration routes, no gaps in the tree line greater than 30 m, use of natural funnels for bats to fly through, and sizing of culverts and underpasses appropriate for the specific bat species, as identified in the pre-construction surveys. The conclusion drawn from the research was the need for interdisciplinary studies to be carried out already during preliminary design work, to ensure a sustainable approach on the part of the road engineers, structural engineers, chiropterologists, and landscape architects involved in the road project. A detailed analysis of numerous factors relevant to the analysed dual carriageway demonstrated the importance of following the principles of sustainable design and collaboration within interdisciplinary design teams to select the best mitigation measures already at the pre-construction stage of the project.

Keywords: bat; sustainability; mesh screens; bat commuting routes; height of flight of bats; land development; mortality rates

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1. Introduction

Bats are a protected species [1–5] and due to the fact that they help maintain the balance in nature, pollinate important plants useful for humans, and feed on insects (crop pests) and nuisance mosquitoes, they have a bearing on human life and on the economy. The need for bat conservation measures is also linked to the species' low reproduction rate (one offspring per year) [6,7]. Many bat species have only one offspring per litter, which, with known bat mortality as a result of infrastructure development, can be a major problem contributing to a decline in some rare and locally scarce populations.

At numerous conferences, chiropterologists exchange information, experiences and projects related to the conservation of these mammals and the sustainable development of infrastructure [8]. Often when designing new roads or wind power plants [9], the existing commuting and migration routes of these useful animals are severed, causing disturbance which requires implementation of the so-called "natural compensations" or special measures in particular with regard to bats [10]. Guidelines for the sustainable design of roads with a particular focus on the protection of bat migration routes have been developed in many countries [11–18]. However, the effectiveness of the applied designs is still under investigation [10,19,20].

Bat commuting routes intersect with both existing roads and the roads that are planned or under construction. When designing wildlife crossings, the main objective is to site the planned crossing structures exactly on the bat commuting route and, first of all, to determine the height that will be adequate to the height of bats' crossing flights over the roads [21–23]. Planning of any wildlife crossing structures should be preceded by a period of monitoring, and the output should be a basis for staking out the possible location of the planned wildlife crossing appropriate for the specific bat species as identified in the survey. This height of flight should be taken into consideration when planning wildlife crossing structures and it should be a basis for designing road solutions serving to extend the bat commuting routes over the road to avoid bat collisions with the vehicles travelling on the road. At the same time, as emphasised by chiropterologists on the basis of the experience gained from the surveys [21,24,25], when designing new roads, particular care should be taken to retain linear habitat features, and to extend them as close as possible to the road edge under construction, as bats use them not only for navigation but also as a protection from predators, wind and also as foraging grounds.

In a sustainable design process, it is also appropriate to analyse the road's importance and the class and the type structure of vehicles travelling on the road [26], as it is necessary to determine the height at which the bats are going to fly over it. On minor two-lane roads, if they cross bat commuting routes, for example, the so-called "natural" wildlife crossings, that is, special groves of a certain shape and height, should be planned. Special wildlife crossing structures and recommendations as to their application are described in detail in [11,12,15,16,27–30].

In Western countries, in similar cases of sustainable road design, it is customary to install "hop-overs" that consist of selected tree species (similar to those found in the area), forming a dense, high canopy [11]. The vegetation of the groves should be appropriately planted in terms of the height both along the commuting route at the closest distance to the road and along the road in question, on both its sides over the entire width of the crossing. Plantings should be sheared at regular intervals to adjust their height to the safe commuting height of the bat species concerned.

Based on many monitoring studies, chiropterologists have estimated that, depending on the species, bats fly both above or within tree canopies and also closer to the ground. At the intersections of the commuting routes with local roads, this mode of flying by bats has been taken into account in the design guidelines [11] recommending "hop-overs" composed of trees of different height raising the height of bat flights over the road to ensure safe passage. Later on, in the Netherlands, attempts were made to construct short screens [11] (only over the length of the intersection of the two routes) instead of planned groves. However, they did not go into use on a wider scale.

As early as in 1991, the first studies on the effectiveness of the use of "hop-overs" were conducted in the Netherlands [30]. The studies focused primarily on the impact of using road lighting along bat commuting routes. It was concluded from the study that trees planted along local roads should have wide crowns to keep the gap between them as small as possible, and should be at least 6 m-high [15,30].

The above issues of bat commuting routes on lit road sections were investigated mainly because bats use the so-called linear landscape features, most often roads, to navigate, especially that in the Netherlands and in Belgium most roads are lit all along the way. Based on bat detector survey results, observation of bat activity, monitoring, and identification and counting of collision fatalities, it was determined [15,30] that road lighting attracts insects to illuminated areas and to bituminous pavements heated up to high temperatures in summer. Additionally, this, in turn, makes low-flying insectivorous bats descend in flight in lit areas while hunting for insects, compromising the safety of road users, as a rule. Taking this into account, the Dutch guidelines [11] first of all recommended the use of “hop-overs” where a linear gap in the forest crosses the road, with supplementary plantings of dense shrubs along the road edge, in order to reduce lighting at the interface between the forest gap and the road. With this type of planting installed directly next to the road, insects did not gather in the dark place at the end of the forest gap, and thus did not provoke bats to lower their flight where the forest gap meets the road. The Dutch guidelines [11] recommended also that mature trees over 6 m in height and having large crowns should be planted in order to minimise the clearance between the trees above the two-lane road.

With regard to the aforementioned problems of road lighting, as there are sections of local roads in suburban areas in France where continuous lighting systems are used, the French guidelines [12,13] recommend simply turning off the lighting over the width of the bat commuting route, which is a much less expensive solution compared to special plantings in the lit forest gap [30], as recommended in the Netherlands. The French guidelines [12,13] recommend that the road lighting system should be extended on both sides of the “hop-over” crossing only up to the edge of the mesh screen or the grove defining the bat flight line.

Equally interesting are the German experiments carried out at the illuminated railway station in Eifel across 1991–1995 [31]. They demonstrated that with an 8 m-long gap in the flight line, 81% of the bats accepted artificial overpass structures hung over the railway tracks that raised the flight height by 2.3 m even if the gap increased up to 16 m, 65% of the bats accepted 8 m-wide and 2.3 m-high underpasses, and only 48% of the bats accepted 5 m-high camouflage netting screens installed on both sides of the road to simulate “hop-overs”.

The experience gained by the Dutch researchers from their studies was also extensively described and analysed in the French guidelines [12,13]. As per the French guidelines [12,13] the “hop-overs” should be additionally provided with mesh screens along their entire length, which can probably keep off low-flying bats from intruding on the roadway. As recommended by the French guidelines [12,13], the minimum height of a mesh screen to be used on two-lane two-way roads should be 2 m, increased up to 6 m on dual carriageway roads. However, there is, as yet, no proven effectiveness of either 2 m or 6 m-high mesh screens in ensuring a safe passage of bats at “hop-over” crossings. In France, the use of mesh screens on bat commuting routes is still being checked to confirm their effectiveness, and it may take several or more years to complete the studies. If higher screens are used, the crossing height can yet increase, which is important for some bat species. Low-flying bats, on the other hand, will treat a 2 m-high mesh screen as an obstacle and may raise their flight height as a result. Based on the output of the conducted studies, the French guidelines recommend [12,13] that the gap in the linear features along the bat commuting route caused by the width of the crossing road should be as small as possible, and hence they recommend the use of supplementary mature tree plantings of at least 6 m in height and having large, branchy crowns extending up to the road edge. In the literature, this extension of natural features such as hedgerows and treelines forming bat flight lines as far as to the road edge is often referred to as a natural funnel for bats to fly through. Recommendations for the use of plantings extending up to the road edge are given, for instance, in the Spanish guidelines [17], based on the assessment of the effectiveness of plantings installed around modified overbridges or culverts, where they served exactly as a natural funnel for some species of commuting bats including *Myotis daubentonii* and *Myotis capaccini*.

Considering the above recommendations and conclusions, it can be summarised that mesh screens of at least 2 m in height are recommended for two-lane roads. As demonstrated by the analysis of bat commuting routes, described in detail in studies [11,32–35], bat commuting routes determined based on bat detector monitoring surveys and complementary visual observations are associated with various linear landscape features, i.e., edges of forest complexes, linear forest gaps, hedgerows, treelines, watercourses or local roads with plantings, which are features used by bats for navigation. At the same time, it should be taken into account that as reported in [10,11,15,21,30,34,36], bat commuting routes can be from over a dozen to several dozen metres wide to correspond to different widths of forest gaps, hedgerows or watercourses. Additionally, at woodland edges, the flight route can be as many as several dozen metres wide, depending on whether it is adjacent to an agricultural area that provides a foraging ground for bats.

In many countries, various structures built over roads were tried, whose direct purpose was to extend the severed bat commuting routes. These include support structures constructed in England [21], timber structures built in the Netherlands [11], spherical structures installed in France [36,37] or natural features using plantings, called “hop-overs”, installed in the Netherlands [11], gantry structures installed in Poland [38], corrugated plate tunnels installed in Germany [39], mesh tunnels hung on trees in England [40] and many other structures [11–13]. Their main purpose is to extend or supplement severed linear landscape features that guide bats to the old migration routes.

As reported in [21,41], the maximum change in the location of the supporting structure built over the road relative to the axis of the old bat commuting route remembered by bats must not exceed 10–15 m. In turn, for roads built on embankments, the maximum diversion to a new bat commuting route leading through a wildlife underpass must not exceed 50 m [13].

It stems from the experience gained by the interdisciplinary project team when designing the mesh tunnel in Alcoi [42] that permanent structures constructed on the bat commuting route cannot also vary in terms of height, for example, in emergency situations, such as damage of the support columns. Taking this criterion into account brought a close cooperation between design engineers, road builders and chiropterologists in the construction of a unique 300 m-long mesh tunnel in Alcoi, Spain. Considering the above conclusions, from the experience gained in the design and operation of the A7 motorway near Alcoi, the Spanish guidelines [10] p. 98, [17] file 14, pp. 89–90, in situations when it is necessary to use structures retaining the height of bats’ crossing flights over dual carriageway roads at a confirmed location of a bat commuting route, recommend the use of mesh tunnels that make bats retain a constant height when flying over the road.

Noise barriers, eco-friendly mesh screens or other barriers [35,43,44] should also be mentioned at this point, along with treelines, as appropriate measures to guide bats to overpasses or underpasses [10,11]. These guiding features are usually more than a dozen or several dozen meters long. Different methods of extending the linear landscape features for bat commuting routes crossing transversely dual carriageway roads are discussed in detail in the guidelines [10–13,17,18]. In the practice of mitigating the impact of roads on bat migration, experimental studies were also conducted in many countries with mesh screens, which were not used to raise the flight height of bats but to guide the commuting bats to underpasses or overpasses [19,45–49]. Based on the experimental study reported in [19], placing the screens on both sides was recommended for *Myotis*, *Plecotus* and *Pipistrellus* bat species, and in particular for *Myotis daubentonii* and *Myotis myotis* species [45,46]. Meanwhile, in the publication [50], based on the experimental research involving the use of 5 m-high camouflage netting screens installed over a length of 50 m, their use was recommended for certain high-flying bat species (for example, *Myotis myotis*). However, the above-mentioned publications and experimental studies refer to a different function of the screens (i.e., the function of guiding bats to under- or overpasses) and not to raising the height of their flight, which is the focus of this article. The studies reported in the above-mentioned publications focused mainly on screens guiding bats to an over- or underpass or raising the height of bat flight over the width of the commuting route (i.e., up to several dozen metres). However, not all the mitigating measures turn out to be effective and functional. In addition, there is a lack of published research on the impact of screens installed along dual carriageway roads over a length of several or more than a dozen kilometres on raising the height of bat flight.

The objective of this article, as intended by the authors, is to identify the determinants of the effectiveness of mesh screens installed along the S3 expressway in Poland, over the stretches of various lengths (several hundred metres and a dozen plus kilometres), whose main purpose was to raise the height of bat flight. In Section 2, the authors discuss the study area, the methods of analysis, and determination of bat mortality, and characterise the design of the mesh screen structures. Section 3 discusses the monitoring results and summarises the roadside mortality values for the three study sections of the S3 expressway (with no screens installed, with mesh screens, or some other screens) and gives also collision site characteristics. In Section 4, the authors discuss the results of the analyses and characterize the main determinants which, together with the mesh screens installed along a dual carriageway road over the length of several kilometres, can contribute to the effective raising of the height at which bats fly across the road. The final conclusions are given in Section 5. A detailed analysis of numerous factors relevant to the analysed dual carriageway demonstrated the importance of following the principles of sustainable design and collaboration within interdisciplinary design teams to select the best mitigation measures already at the pre-construction stage of the project.

2. Materials and Methods

2.1. Study Area

The first feasibility studies to upgrade the National Road No. 3 in Poland to the expressway standard began in the 1980s. At that time, the road was a part of the basic road system of Poland's western borderland. While the route of the planned road was included in many local development plans, the scope of the completed work was very limited due to the economic difficulties of the late 1980s. The engineering work was resumed in 1992 as part of Poland's motorway construction programme; however, comprehensive design work for the planned S3 expressway got underway much later, i.e., in 2004 [33]. On the S3 expressway, the maximum allowed speed of travel is 110 km/h [33] with the following traffic volumes measured in 2015: 14,184 veh./24 h on sections No. 1 and No. 3 and 14,435 veh./24 h on section No. 4 [51]; and in the years 2020–2021: 20,448 veh./24 h on sections No. 1 and No. 3 and 19,638 veh./24 h on section No. 4 [52].

When working on the S3 expressway design, it was found [33] that the expressway's route crosses bat foraging and migration areas situated in the western part of Poland (the Nietoperek Special Habitat Protection Area—hibernaculum) and, therefore, some mitigation interventions should be developed to ensure bat protection along their commuting routes. Figure 1 shows the study area (coordinates: from 52°35′4.63″ N, 15°27′15.02″ E—MD-14 Bridge to 52° 3′52.39″ N, 15°36′55.70″ E—Sulechów Junction):

S3 expressway—Gorzów Wlkp.—Międzyrzecz North road junction:

- Study section No. 1—from km 18 + 040 to km 25 + 500—from 52°35′4.63″ N, 15°27′15.02″ E to 52°33′39.18″ N, 15°31′19.58″ E,
- Study section No. 3—from km 25 + 500 to km 37 + 146—from 52°33′39.18″ N, 15°31′19.58″ E to 52°28′42.90″ N, 15°33′13.69″ E.

S3 expressway—Międzyrzecz South road junction—Sulechów road junction

- Study section No. 4—from km 32 + 300 to km 42 + 953.96—from 52°28′42.90″ N, 15°33′13.69″ E to 52° 3′52.39″ N, 15°36′55.70″ E.

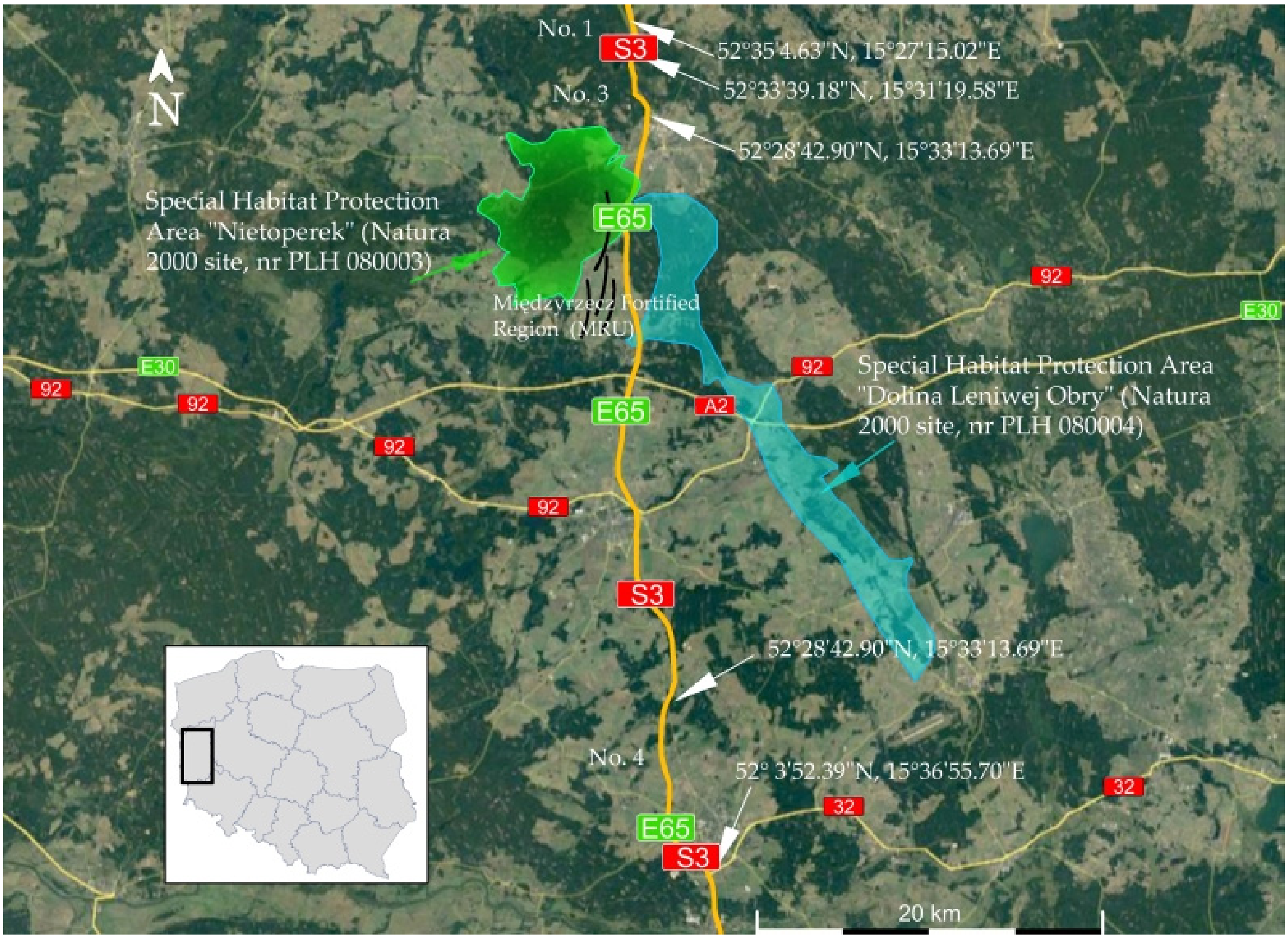


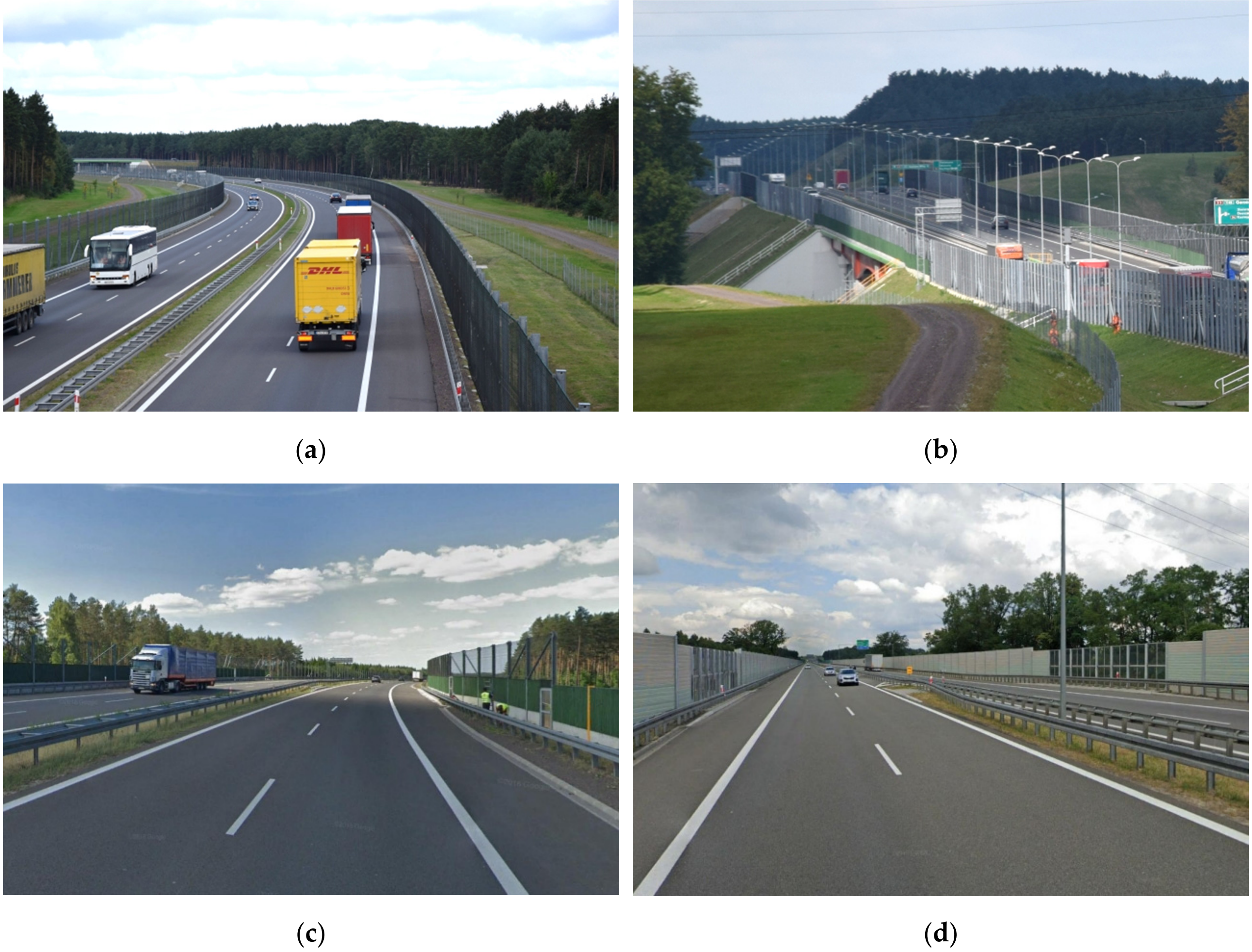
Figure 1. Map of the studied area showing the location of the S3 expressway in western Poland, (visualisation prepared by the authors, pictured against a satellite image from Google Earth [53]).

Based on the results of the pre-construction surveys [54], their authors concluded that “at night individuals from a single bat colony forage in a widely dispersed manner, thus avoiding intraspecific competition”. The research confirmed also the commuting routes along the prominent linear landscape features such as treelines, overgrown field baulks, streams, rivers, local roads with trees lining up next to them. Taking this into account, particularly due to the considered extensive Nietoperek bat reserve impact, the areas along these linear features where bats transversely cross the S3 expressway may be the sites of higher bat mortality.

In studies on the impact of traffic volumes, and levels of noise and lighting recorded on expressways, many researchers [23,26,29,30,55,56] confirmed that these factors can have an effect on potential bat mortality, particularly in open areas with trees less than 6 m-tall. These studies also stated that potential bat–vehicle collision sites are located where linear landscape features cross the highways. Taking the above into account, protection measures for hiropterofauna in the form of various types of screens were provided for the places of potential collision risk within the protection area on the S3 expressway (Figure 2). Mesh screens, noise barriers or other elements were deployed there, depending on the local environmental needs at the site (Table 1).

Table 1. Siting of a 4 m-high screen on the S3 expressway in the study area (authors' own data from the site inspections).

Study Section	**Type of Screen/Barrier on Side W—West and E—East**	**Start of Screen, km**	**End of Screen, km**	**Length of Screen, m**	**Start of Screen, km**	**End of Screen, km**	**Length of Screen, m**
		Western Side (W)			**Eastern Side (E)**		
No 1	mesh screen on both sides	18 + 350	18 + 700	350	18 + 350	18 + 700	350
	type EA-10A on both sides	18 + 700	18 + 995	295	18 + 700	18 + 995	295
	mesh screen on both sides	18 + 995	21 + 600	2605	18 + 995	21 + 600	2605
	mesh W and type EA-17 E	21 + 600	21 + 760	160	21 + 600	21 + 760	160
	type EA-17 and E-18	21 + 760	21 + 840	80	21 + 760	21 + 840	80
	type EA-17 on one side E	–	–	–	21 + 840	23 + 260	1420
	type EA-19 W and EA-17 E	23 + 260	23 + 341	81	23 + 260	23 + 341	81
	type EA-17 on one side E	–	–	–	23 + 341	23 + 486	145
	Type EA-11 W and EA-17 E	23 + 486	23 + 566	80	23 + 486	23 + 566	80
	mesh screen on one side E	–	–	–	24 + 150	24 + 500	350
No. 3	mesh screen on both sides	27 + 550	27 + 730	180	27 + 550	27 + 730	180
	mesh screen on both sides	27 + 730	27 + 850	120	27 + 730	27 + 850	120
	mesh screen on one side E	–	–	–	27 + 850	27 + 900	50
	mesh screen on both sides	27 + 900	28 + 230	330	27 + 900	28 + 230	330
	mesh screen on one side W	28 + 230	28 + 280	50	–	–	
	mesh screen on one side E	–	–		28 + 280	28 + 300	20
	mesh screen on both sides	28 + 300	32 + 269	3969	28 + 300	32 + 269	3969
	type EA-14 on both sides	32 + 269	32 + 397	227	32 + 269	32 + 397	227
	mesh screen on both sides	32 + 397	32 + 624	227	32 + 397	32 + 624	227
	type EA-15 W and mesh E	32 + 624	32 + 635	11	32 + 624	32 + 635	11
	type EA-15 on both sides	32 + 635	32 + 684	49	32 + 635	32 + 684	49
	mesh W and type EA-15 E	32 + 684	32 + 696	12	32 + 684	32 + 696	12
	mesh screen on both sides	32 + 696	35 + 550	2854	32 + 696	35 + 550	2854
No. 4	mesh screen on both sides	32 + 940	33 + 830	890	32 + 940	33 + 940	890
		34 + 250	34 + 450	150	–	–	–
	mesh screen on both sides	34 + 400	34 + 450	50	34 + 400	34 + 450	50
	mesh screen on both sides	35 + 500	35 + 900	400	35 + 500	35 + 900	400
	mesh screen on both sides	37 + 900	38 + 200	300	37 + 900	38 + 200	300
	mesh screen on both sides	38 + 700	39 + 100	400	38 + 700	39 + 100	400
	mesh screen on one side W	39 + 100	39 + 300	200	–	–	–
	noise barrier on one side E	–	–	–	40 + 983	41 + 140	160
	transparent on one side E	–	–	–	41 + 140	41 + 197	56
	noise barrier on one side E	–	–	–	41 + 197	41 + 271	74
	mesh screen on one side E	–	–	–	41 + 271	41 + 280	9
	mesh screen on both sides	41 + 280	41 + 621	341	41 + 280	41 + 621	341
	noise barrier W and mesh E	41 + 621	41 + 948	327	41 + 621	41 + 948	327
	noise barrier on both sides	41 + 948	42 + 548	600	41 + 948	42 + 548	600
	noise barrier on one side E	–	–	–	42 + 548	42 + 633	85



(**a**) (**b**) (**c**) (**d**)

Figure 2. Screens installed on the S3 expressway: (**a**) an example of 4 m-high mesh screens; (**b**) an example of various types of screens: 4 m-high mesh screens and mixed screens used on bridges or overpasses (2 m-high EA-17 and EA-18 noise barriers and 2 m-high mesh screens); (**c**) examples of a 2 m-high EA-15 timber noise barrier combined with a 2 m-high mesh screen (Source: Google Earth [53]); (**d**) an example of a 4 m-high noise barrier (Source: Google Earth [53]).

2.2. Characteristics of the "Nietoperek" Special Habitat Protection Area

The Nietoperek Special Habitat Protection Area (Natura 2000 site No. PLH 080003) comprises an extensive network of old underground fortifications, including some 30 km of reinforced concrete tunnels located 30–50 m below the ground surface and an area of the corresponding size on the surface. Battle shelters together with the system of underground corridors constitute a unique heritage fortification structure. The reserve's area is 50.77 ha [57]. The tunnels are a part of the so-called Międzyrzecz Fortified Region (MRU), a fortification complex built during the 1933–1945 period. The underground spaces are connected to the surface by a few vertical ventilation shafts and corridors leading to bunkers. Favourable microclimatic conditions, the vast extent of the underground spaces, and the abundance of various hideouts provide many bat species with optimum conditions for hibernation. Bats from as far as Mecklenburg and Brandenburg flock to MRU for winter dormancy [57]. The distribution of bats over the MRU underground is not uniform. The greatest numbers of wintering bats were found in the corridors located in the northern part of the MRU complex.

The Nietoperek reserve is the most important wintering and breeding ground for a multispecies colony of bats [57] in Central Europe, with a population of 20,000 wintering bats according to 1997 data [58], of over 30,000 individuals in 2005, 36,900 individuals in 2007 [59], and over 40,000 individuals in 2016 [60], belonging to at least twelve species, including four protected ones, listed in Annex II to the Habitats Directive [2]. As reported in [33], the following protected bat species winter in the hibernaculum: *Barbastella barbastellus*—1200–1500 individuals, *Myotis dasycneme*—15–20 individuals; *Myotis bechsteini*—20–30 individuals; and *Myotis myotis*—14,500 individuals. The most abundant species recorded in the "Nietoperek" hibernaculum were [35]: *Myotis daubentoni*, *Myotis myotis*, *Plecotus auritus* and *Myotis natteri*. Based on the studies carried out, the report [33] concluded that disturbance caused by people entering underground tunnels is the primary threat to bat hibernation. Taking the above into account, the entrances to the tunnels were locked for the period of the bats' winter dormancy.

2.3. Methods

Under the current rules [33], post-construction monitoring of bat mortality was conducted on the new S3 expressway over the three years following its opening for traffic on a total of three study sections of varying lengths [60,61].

Two monitoring methods are customarily used to test the effectiveness of ecological measures used to ensure bats' safe crossing over roads: acoustic detection and visual observations. Both these monitoring methods are of little use in the investigation of the effectiveness of mesh screens, the main purpose of which was to raise the flight height of bats, as the screens are of considerable length and are not a transverse point-type obstacle on their flight route. Therefore, a third method was used in the monitoring surveys [60,61] involving identification and counting of collision fatalities (sampling method focusing on the location of small carcasses) found on the carriageway, emergency lanes and shoulders along all three study sections. The third method was used because of the specific habitat requirements, the varying screen lengths and the proximity to the proposed Skwierzyna Natura 2000 site and the Nietoperek site of the Natura 2000 network [33,60,61].

All the three reports [33,60,61] assume that identification of bat carcasses would be made during a tour along the carriageway on both sides of the road. In addition to the exact location of a dead bat found, the survey recorded the date on which the carcass was found and the weather conditions (i.e., temperature, wind speed and the degree of cloud cover).

In the course of the monitoring, the identified dead bats were removed from the study area to avoid recounting the same individuals in future surveys. Surveys were conducted outside the bat hibernation period, during the breeding season and during their peak activity, from April to November, every seven days, three hours after sunrise. Given the need to conduct surveys after rainless nights, the daytime schedule was slightly revised, every 9 or 5 days [60,61]. The surface of the carriageway, central reservation and dirt shoulders were inspected with binoculars, and if a bat carcass was found, a thorough examination was carried out. The species, sex and age of the bat were determined if possible (depending on the condition of the dead bat), the location of the find was photographed and the exact chainage of the road was identified (using GPS equipment), and the side of the road and the location in the cross section were assigned to it. In a few cases it was not possible to determine their species, sex and age due to the deteriorated state of the carcass.

However, it should be stressed that the monitoring data obtained from dead bat identification are not fully reliable, as bat carcasses may be scavenged by wild carrion-feeding animals or undergo natural decomposition (which happens more rapidly during hot summers) [10,62–64]. Still, given the existing fencing of the S3 expressway and the screens installed, it can be assumed that the measurement error in the surveys was significantly less than that recorded on two-way two-lane roads without fences or screens [62–64].

In addition, the report [60] pointed out that the quantitative differences between the individual surveys may have been caused by different temperatures in the individual years. However, these observations and the corresponding proportionality in the fatality counts were not confirmed in the conclusions of the report [61] from the surveys conducted in the same years on the following section of the S3 expressway. Perhaps the difference in results obtained in different years was, to a certain degree, due to the behavioural habits of the bats which abandoned the old routes they had been using before and during the construction phase and which they returned to after completion of the work.

To identify the determinants allowing authors to ascertain whether the mesh screen had proved effective in reducing the bat mortality, they decided to carry out the analyses of the local geography of the road at locations where the numbers of bat carcasses found were higher than in other locations. It was assumed that one dead bat would not prove the ineffectiveness of a screen installed at a particular location. However, two or more carcasses found in a similar location should trigger a detailed analysis of the local geography of the road on both its sides. For instance, it was assumed that the likely bat commuting routes existing until the start of construction, at places where they crossed the S3 expressway, would be analysed. In accordance with the recommendations given in the guidelines [11,17,18] and the conclusions set out in the publications [10,19–22,36–38,43,44] on completion of the road construction work, when analysing the determinants, particular attention would be paid in particular to retaining the continuity of linear landscape features used by bats for navigation. In accordance with the recommendations of the guidelines [11,17–20], new trees or hedges should be planted along the bat commuting route to provide a natural funnel channelling bat movements and extended directly to the edge of the expressway, and where appropriate, of the screen. The applied method is presented in Figure 3.

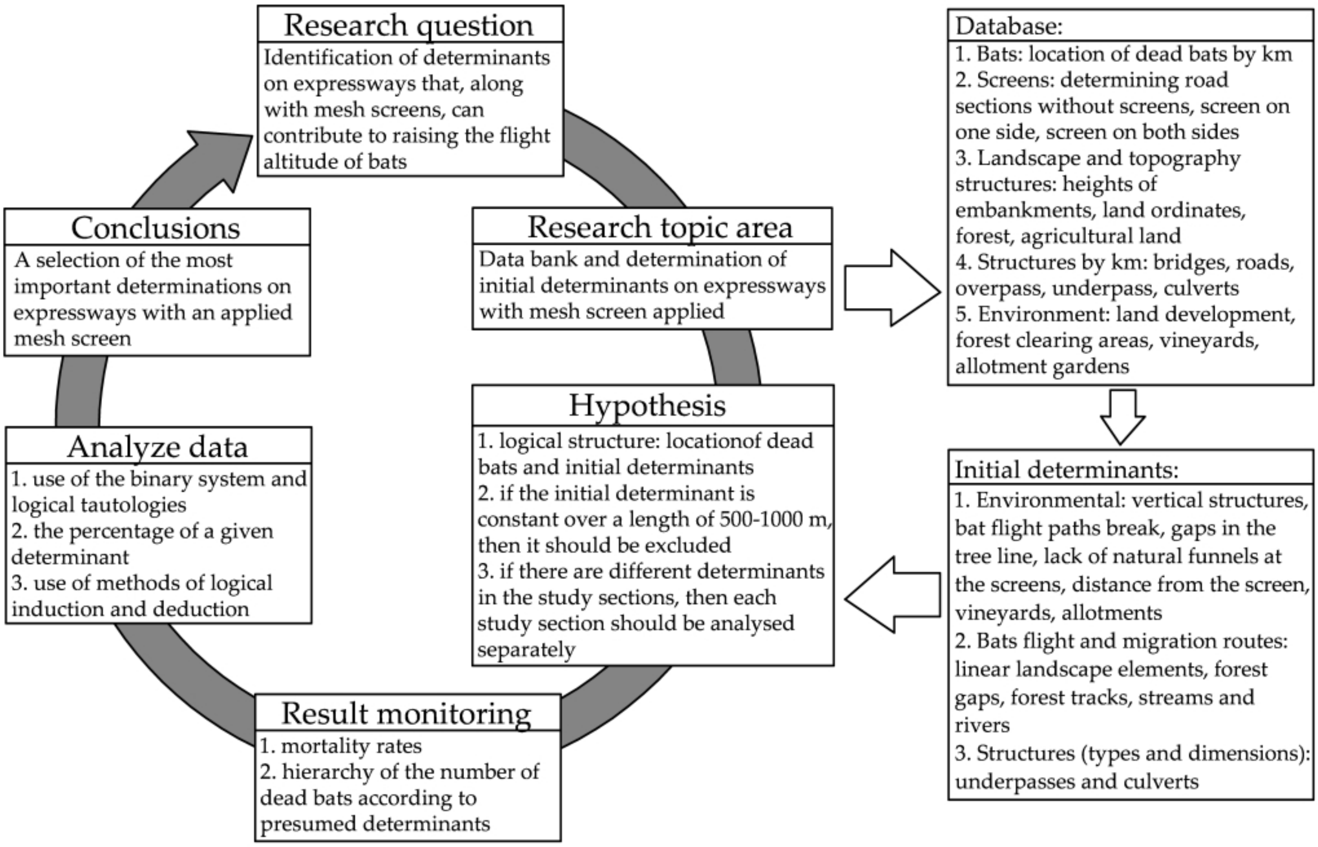


Figure 3. Step-by step method.

Additionally, this condition of extending the supplementary vegetation guiding bats up to the screen was given special attention by the authors of the article when identifying the determinants of the effectiveness of the mesh screens under analysis. In line with the conclusions of the publications [10,19,36–38], the height of the new trees or hedges and the continuity of the type of guiding features are also important, as different bat species have their commuting routes at specific altitudes. Based on the bat species determined in the pre-construction monitoring mainly in sustainable road construction, the aim is to retain the vertical structures, landscape and topography along the existing bat commuting routes. Figure 3 shows some examples of failure to retain the continuity of linear features in the case of wildlife underpasses or culverts (Figure 4a), and of a forest clearance along a side road carried by an overpass, and thus of a severed continuity of the bat flight lines (Figure 4b).

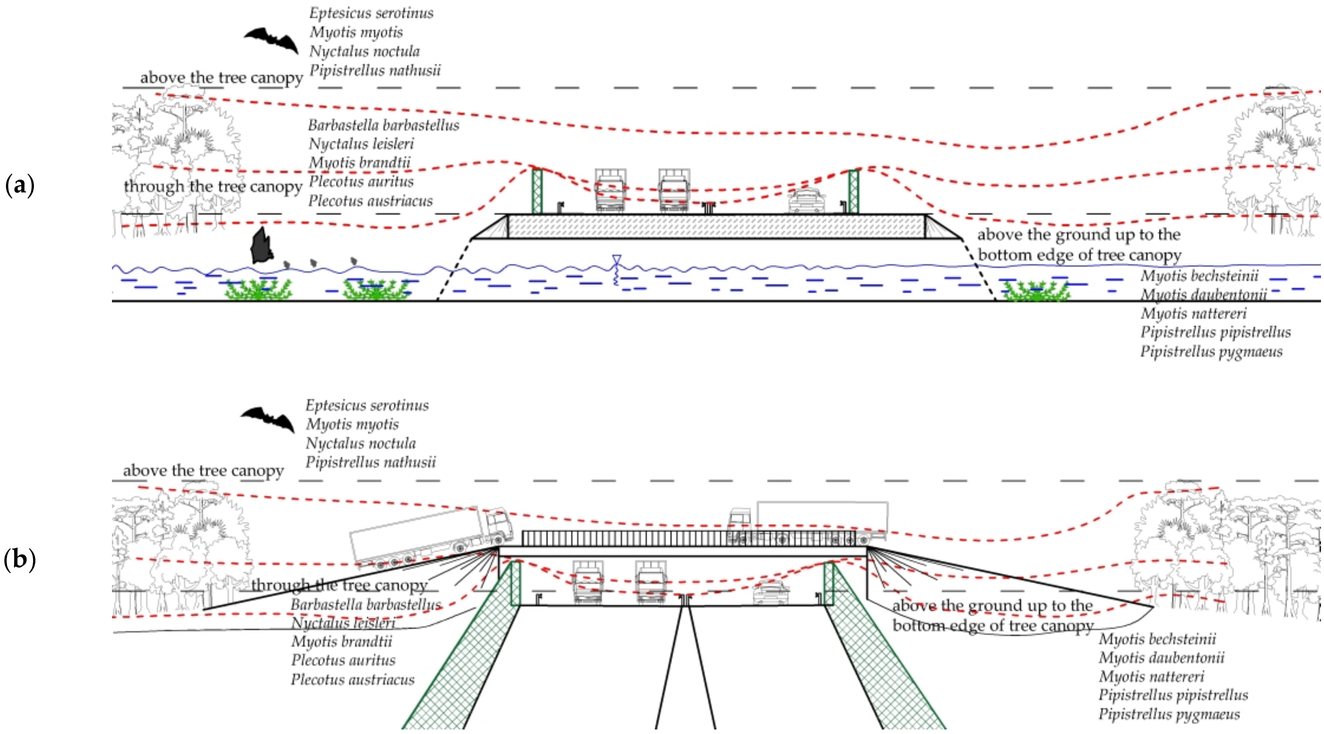


Figure 4. Probable changes in the altitude of flight of bat species confirmed by monitoring due to severed linear landscape features, over a ca. 120 m-wide right-of-way: (**a**) When the expressway is crossed by a culvert or an underpass; (**b**) When the expressway is crossed over by a transverse road running on an overpass.

2.4. Modelling of the Altitude of a Bat Flight Route Using a 4 m-High Mesh Screen

On the basis of the available plans of the expressway [33], in the analyses described in this article, the height of the mesh screens erected along the road was assumed to be 4 m. The S3 expressway authority decided to erect 4 m-high screens based on the opinion of Prof. Jakubiec [54], assuming them to be the most effective form of protection of bats against collisions with traffic. It was expected that following the installation of the 4 m-high screens, bats would raise the altitude of their flight and probably cross at a safe height of several metres over the expressway. The mesh screens were installed at the indicated locations based on the preliminary findings of the chiropterologists on the basis of the monitoring studies [33,54]. At road structures where 2 m-high noise barriers were initially planned, 2 m-high mesh screens were additionally installed, and at other locations, other screens, also 4 m-high, were provided to address various other needs [61,65,66]. An analysis of the height of the screens erected on the S3 expressway, taking into account the flight height of various bat species, is presented in Figure 5. The species considered in the analysis were based on the data obtained from monitoring surveys [60,61]. The bat flight height data for the bat species shown in Figure 5 were taken from an analysis of the data presented in the publications [10,67–73].

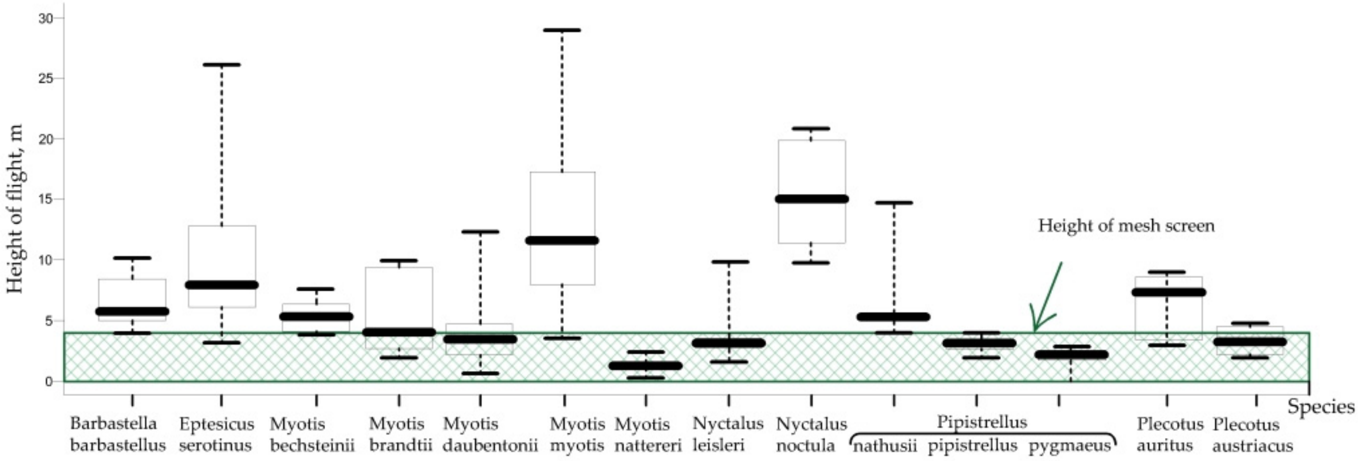


Figure 5. The height of flight of bat species identified during bat mortality surveys conducted on the S3 road. The whiskers represent the minimum and maximum values; lower and upper edges of the boxes determine the first and third quartiles; the bold line designates the median value.

2.5. Results of Various Investigations of Movement Trajectories along Bat Commuting Routes

As part of the study on the correlation between the changes in the landscape and land development features around a new road under construction and the activities of individual landowners, a study on the impact of the length of a gap in the linear landscape elements on the frequency and height of bat flights was conducted in France [74]. It is customary for the owner of a new road to carry out an environmental impact assessment, at the pre-construction design stage, which is limited to estimating the impact of the project, however. The measurable effects of the road on the natural environment can therefore only be assessed as part of the post-construction surveys. In the studies reported in [10,74], the authors considered bat commuting routes in consolidated and unconsolidated areas, along linear landscape features with gaps of different lengths (up to 20 m, up to 30 m, and up to 40 m and longer). At the locations selected for the study, pre- and post-construction observations of bat flight frequency were conducted over the same period of the year. As a result of the surveys [10,74] among other things it was confirmed that: bat activity is approximately halved in consolidated areas and that a gap in a hedgerow of up to 20 m in length does not reduce bat flight frequency, while at gaps in linear landscape features greater than 40 m, bat activity is significantly reduced, which may suggest that they are perceived by bats as open areas.

The above conclusions not only apply to flight navigation in the areas surrounding a new road under construction, but they are also crucial for retaining the continuity of the bat flight lines in the immediate vicinity of underpasses [10–12]. By retaining an appropriate vertical clearance under the underpass and extending the guiding vegetation up to the underpass, the authors of the study [75] confirmed that bats that habitually fly within or near vegetation would prefer underpasses over culverts or flights over the road. In turn, bats flying in open airspace are more likely to fly over the road, and thus additional structures are needed to raise their flight height in this case (this includes also the bat species considered in this article, such as *Barbastella barbastellus*, *Eptesicus serotinus*, *Nyctalus leisleri* and *Nyctalus noctula*) [19,75].

Currently, state-of-the-art devices, such as thermal or infrared cameras, are used to study bat migration, allowing the analysis of bat flight and behaviour in the recorded images [10]. These trajectography techniques, still in the experimental phase, allow reconstructing the bat's movements by specialization of the sounds it produces. The research results published to date [10,76] were used to develop the hypothesis on the flight routes on overpasses spanning dual carriageway roads (Figure 6).

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

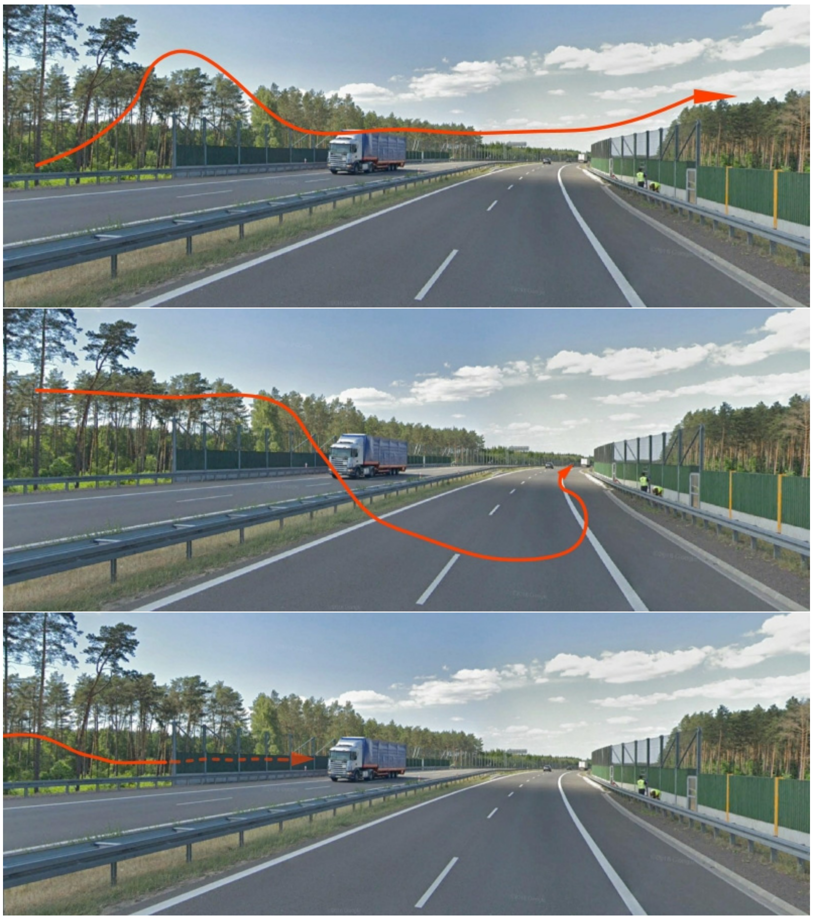
Figure 6. A hypothetical visualisation of a bat flight trajectory along the old route of a local road newly constructed on an overpass bridge over a newly completed dual carriageway: (**a**) View of a hypothetical bat flight route from the local road on the overpass bridge with no additional guiding elements; (**b**) Aerial view of a bat flight route along the overpass and further along the S3 expressway with mesh screens installed on both sides. (Visualization by the authors based on the description of the research and conclusions given in [76]).

As regards bats that fly high above the tree canopies, investigations carried out with a thermal imaging camera demonstrated [10] that a bat can descend as low as 0.75 m above a dual carriageway surface while hunting, thus flying at a height posing a risk of direct collision with a vehicle travelling down the road. However, this risky behaviour is practically impossible to predict at the planning stage of the project. Following surveys of bat flight trajectories with screens installed on both sides of the S3 expressway, the authors of the report [60] observed five types of bat behaviour. Their graphic interpretation is given in Figure 7. The patterns of the presented characteristic movement trajectories agree in general with the results of other surveys conducted at transverse obstacles, e.g., steel structures [21,32] or spherical structures [36,37]. As regards Case V shown in Figure 7, the authors of the report [60] proposed a hypothesis that such behaviour can be linked mainly to the presence of the mesh screen installed on the timber barrier, as the openwork screens absorb heat during the day to give it off during the night, thus attracting insects that are an easy prey for small bats of the *Myotis* and *Pipistrellus* species.

Case I—safe behaviour
The *Nyctalus* and *Myotis* bat species flying at the tree canopy height, flying over the dual carriageway without lowering their flight and crossing over the screens and carriageway at a safe height.

Case II—safe behaviour
Low-flying *Nyctalus* and *Myotis* bat species raise their flight over the screen and fly over the road at a safe height.

Figure 7. *Cont.*



Case III—risky behaviour
The *Pipistrellus* bats, having flown over the screen, lower their flight over the roadway (they are then at collision height) and only raise their flight before the screen on the other side of the road to fly over it.

Case IV—risky behaviour
The *Pipistrellus* bats, having flown over the screen, lower their flight over the road and continue along the road (often at collision height).

Case V—behaviour typical of mainly small *Myotis* and *Pipistrellus* species bats.
These bats fly close up to the screen and continue their flight along it without crossing the road.

Figure 7. The types of bat behaviour observed on the S3 expressway with a 4 m-high combination mesh screen and timber noise barrier. (Visualisation by the authors based on the survey reported in the report [60]). The arrow marked the direction of flight.

The behaviour of bats in the vicinity of the mesh screens installed along the S3 expressway also supports the conclusions from the studies described in [19] and the subdivision of European bat species into 5 functional groups. Conclusions from the studies described in [19] also formed a basis for establishing certain determinants, concerning, among other things, functional behaviours of bats and the associated size of the inside clearance distances of culverts or underpasses.

2.6. Structural Details of Mesh Screens

The mesh screen structure consists of polystyrene netting of min. 40 kN/m tensile strength [65,66], spanning between upright S355J0 steel posts (Figure 8). The netting is hung from steel cables anchored to steel posts. The steel posts are I-beams and square hollow sections, anchored to the pile-type foundations. In addition, based on structural calculations [65,66], square hollow section braces were used only at the posts that anchor the steel suspension cables (one bracing at the end posts and two bracings at the intermediate posts). The steel suspension cables are anchored at a height of 0.3, 2.1 and 4.1 m above the ground level spaced at max. 40 m intervals [65,66]. The intermediate posts supporting the mesh are spaced at 4 m intervals. All the steel components of the posts and the cables are protected from corrosion by metal spraying and suitable coatings. The screens are protected from being hit by vehicles with safety barriers. The impact was assumed to be an extraordinary situation and thus the mesh screen support structure was not designed to withstand the resulting load.

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

Figure 8. Structural details of mesh screens: (**a**) View of the S3 expressway with mesh screens on both sides; (**b**) Steel posts with braces.

The mesh size and the width of the mesh strand were selected in [65,66] taking into account the fact that the bat's navigation system detects an obstacle in form of a fence and makes the bat change the direction or height of its flight. The maximum size of the mesh aperture is $h \times b = 5 \times 5$ cm [65,66]. The chosen mesh size prevents birds from getting caught in the netting. The screens are, as a rule, positioned at a distance of 1.35 m from the edge of the carriageway (i.e., 0.85 from the face of the safety barrier) [65,66]. Only at the locations of road signs were these distances made slightly greater in order to ensure the required clear width of the road.

To ensure safety of the motorists travelling along the S3 expressway and the maintenance and other services, easily dismantled screen panels of a contrasting colour were installed at 200 m intervals (Figure 9).

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

Figure 9. Emergency exit: (**a**) Stairs and landing to allow evacuation of the road users in case of emergency; (**b**) Easily removable safety mesh netting at an emergency exit point.

Considering the road maintenance requirements and the safety considerations of travellers, several emergency exit points for road maintenance vehicles were provided on these several kilometre long sections of the expressway that had been lined with mesh screens (Figure 10). The whole of the exit gate was also protected with polystyrene mesh, identical to that used in the mesh screen construction.

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

Figure 10. Exit gate on the expressway section with mesh screens: (**a**) Ramp off to the service road; (**b**) Safety mesh netting on the exit gate.

3. Results

3.1. Results of the Monitoring Survey of Chiropterofauna on the S3 Expressway on Section No. 1: From km 18 + 040 to km 25 + 500 in the Period 2014–2016

This article uses the data from the monitoring survey of the S3 expressway in service obtained over the 2014–2016 period and presented in [60]. Section No. 1 is 7.15 km-long and it was provided with 350 m-long screens installed on one side only and 3.060 km of screens installed on both sides of the road. The screen siting details are given in Table 1. The report [33] identifies the likely bat commuting routes to foraging grounds by designating, for example, forest edges, watercourses, linear forest gaps and local roads lined with trees or hedgerows. The identified locations along the road were protected with mesh screens. In total, fourteen fatalities were confirmed in the bat mortality monitoring survey conducted over the 2014–2016 period [60], including eight in 2014, three in 2015 and three in 2016. The distribution of bat carcasses found along Section No. 1 of the road is shown in Figure 11.

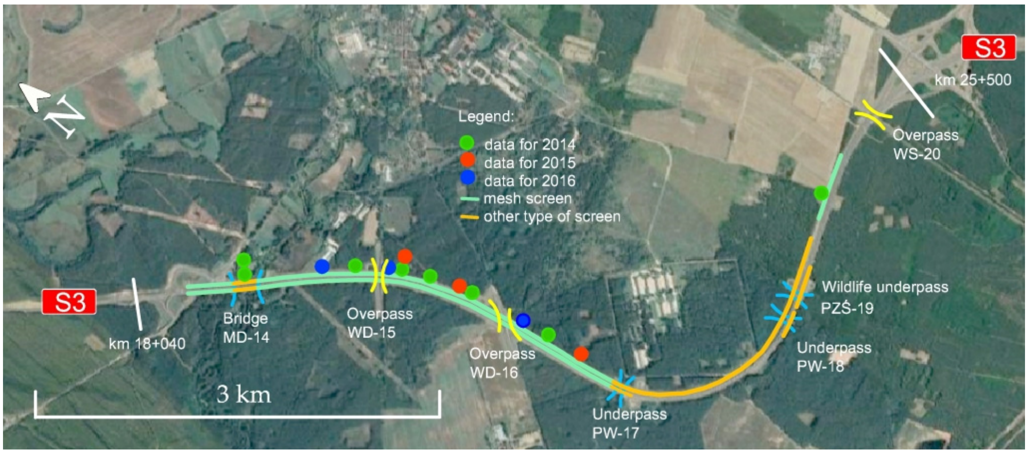


Figure 11. Locations of bat carcasses, screens and road overpasses, underpasses and culverts along the study section No. 1 of the S3 expressway. (Visualisation by the authors based on bat mortality data given in the Reports [60]).

The data show that single dead bats were found at various locations along the S3 expressway with and without screens in place. There were only two locations where two carcasses were found. The first location was on the existing migration route near the bridge over the Obra (Appendix A—Figure A1). There are 4 m-high screens on both sides of this bridge. Both noctule bat (*Nyctalus noctula)* carcasses were found in 2014, shortly after the road was opened for traffic. Given the height of *Nyctalus noctula's* flight, it was probably a result of a hunting bat's collision with a vehicle, as there is a foraging area under the bridge in question. Noteworthily, in that specific case, due to the natural response of a hunting bat to an environmental stimulus, there are no effective and economical ways to eliminate the risk. However, as regards low-flying species, the screens used on the bridge over the Obra River are deemed a satisfactory measure.

The other location where the finding of bat carcasses in the years 2014–2016 was confirmed was the S3 expressway's intersection with a suburban street located on the overpass spanning the S3 expressway (Appendix A—Figure A2). An analysis of the landscape and land development features around the new road indicates that the construction stage was not completed by the extension and restoration of linear landscape features used by bats for navigation. It needs to be noted that after the completion of the S3 expressway, the slopes of the embankment on which the transverse street runs do not serve as linear features for bat flight navigation. Still, the nearby storm pond is a good foraging ground. The mesh screen installed along the S3 expressway (positioned on the lower level) and along the length of several linear forest gaps is not accompanied by any supporting plantings along the treeline on both sides of the road or by any natural funnel for bats to fly through. Thus, the screen is just an abrupt obstruction on the lowered ca. 120 m-wide commuting route. The identified gaps in the linear features of the surrounding landscape and a lack of the guiding funnel most probably made the bats lower their fly height resulting in the identified vehicle–bat collisions shown in Figure 4a,b.

3.2. Results of the Monitoring Survey of Chiropterofauna Conducted on the S3 Expressway on Section No. 3: From km 25 + 500 to km 37 + 146 over the 2014–2017 Period

In section No. 3, mesh screens prevail by a large margin. In this specific case, noise barriers or other types of barriers were installed only at the intersections with the local roads and mesh screens were installed on top of them, thus achieving a uniform screen height of 4 m all along the section. The study section No. 3 is over 11.6 km-long with the screens on both sides totalling 7.88 km in length. In study section No. 3, a total of 25 bat carcasses (Figure 12) [60] were recorded during the bat mortality monitoring survey conducted over the 2014–2016 period. This number of carcasses included: *Nyctalus noctula*—10 No.; *Pipistrellus pipistrellus*—10 No.; *Myotis nattereri*—2 No.; and *Myotis myotis*, *Plecotus auritus* and *Myotis daubentonii*—1 No. each.

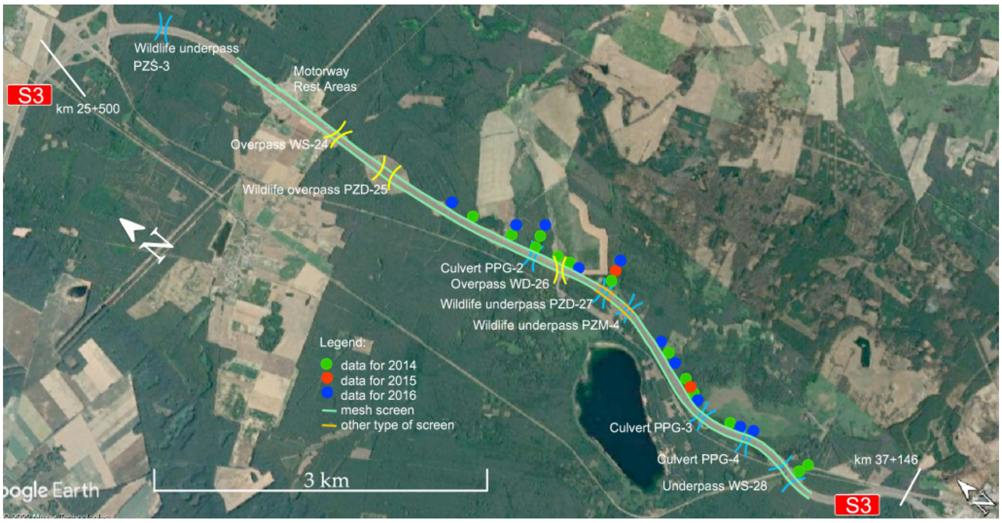


Figure 12. Location of bat carcasses, screens and road overpasses, underpasses and culverts along the study section No. 3 of the S3 expressway. (Visualisation by the authors based on bat mortality data given in the reports [60]).

The carcass distribution analysis showed (Figure 12) that in almost all cases, dead bats were found in the vicinity of underpasses or culverts. Where greater numbers of carcasses were found, in two cases it was an underpass, in one case it was a culvert, and in the fourth case it was a severed forest road (Appendix B—Figure A3).

A detailed analysis of the landscape and land development features on both sides of the road demonstrated that at the above indicated locations on potential bat flight routes, severed linear landscape features had not been restored. Additionally, no additional plantings extending up to the screen face and forming the so-called natural funnel for bats to fly through had been provided, and natural patches of vegetation, i.e., hedgerows, shrubs, groves or treelines, ended 30–200 m from the edge of the S3 expressway. These additional supplementary plantings in the form of a natural funnel are recommended in recent publications and in current design guidelines [10,11,17–21,23]. The authors believe it is those deficiencies in the filling of the gaps in the linear landscape elements and the lack of a natural funnel channelling the bats in flight that could have contributed to: the lowered height of bat flight on the approach to the S3 expressway and, in consequence, to the identified collisions with vehicles. These observations harmonize with the cases presented in Figure 3.

3.3. Results of the Monitoring Survey of Chiropterofauna on the S3 Expressway Conducted on Section No. 4: From km 32 + 300 to km 42 + 953.96 over the 2014–2017 Period

In the last study section, No. 4, the screens were not installed in a continuous system, as was the case in sections No. 1 and No. 3, but they were erected in designated places based on pre-construction monitoring data [33] (Table 1). Section No. 4 is over 10.6 km-long. The total length of the screens installed on one side of this road section was 760 m, while the total length of the screens installed on both sides of the road was over 3.3 km. The bat mortality monitoring survey conducted over the 2014–2017 period yielded a total of 58 no. of bat carcasses found throughout the entire length of the study section No. 4 [61]. The number included: carcasses of *Pipistrellus pipistrellus*—18 No.; *Nyctalus noctula*—8 No.; *Myotis brandtii*—7 No.; *Myotis myotis*—4 No.; *Eptesicus serotinus*, *Plecotus austriacus*, *Pipistrellus pygmaeus* and *Myotis bechsteinii*—2 No. each; and *Pipistrellus nathusii*, *Plecotus auritus*, *Nyctalus leisleri* and *Barbastella barbastellus*—1 no. each. The species of nine bat carcasses were not identified [61].

An analysis of the distribution of the bat carcasses found along study section No. 4 shows (Figure 13) that, in almost all cases, the locations at which several dead bats were found were in the vicinity of wildlife overpasses or underpasses under the expressway, and near several culverts without screens or near culverts with screens yet without a natural funnel (Appendix C—Figure A4).

In two cases, the carcasses were found in the surroundings of rail and road underpasses on the S3 expressway with no screens installed, although they probably could have served as linear landscape elements, providing a major navigation aid for bats (Appendix C—Figure A5a). However, the largest number of bat carcasses, accounting in total for 1/3 of all fatalities, were found on the stretch of this study section of the S3 expressway with mesh screens or noise barriers installed, located in the vicinity of a vineyard, forest, the Sulejówka and its tributary or garden allotments, which are extensive and very diverse foraging grounds (Appendix C—Figure A5b).

In two cases, bat carcasses were found along lit S3 expressway segments, i.e., within rest area (Appendix C—Figure A6) and along a stretch of the approach road to the interchange. Figure A6 in Appendix C shows: probable bat commuting routes along the edges of the forest forming linear landscape features in 2010 (red dotted line) and locations of bat carcass finds (orange cross mark), as well as the landscape and land development features within the expressway rest areas and the location of mesh screens in 2016, at the time when bat carcasses were found. An analysis of the distribution of screens and of the probable commuting route, with different bat species confirmed, indicates significant gaps in linear navigation features and the absence of a natural funnel. This section runs in a cutting with the edge of the forest situated 90 m away from the embankment slope crest on the eastern side and 35 m on the western side. The distance between the cutting slopes' crests is 55 m. Thus, the gap in the flight line at the southern end of the mesh screens is 180 m, i.e., according to the research conclusions formulated in [10,19,74], bats treat this area as an open terrain. Additionally, at the northern end of the installed mesh screens, there is no continuity of linear landscape features. The lighting at the rest area attracts many insects, which, in turn, attract foraging bats to areas where they face the risk of collision with vehicles.

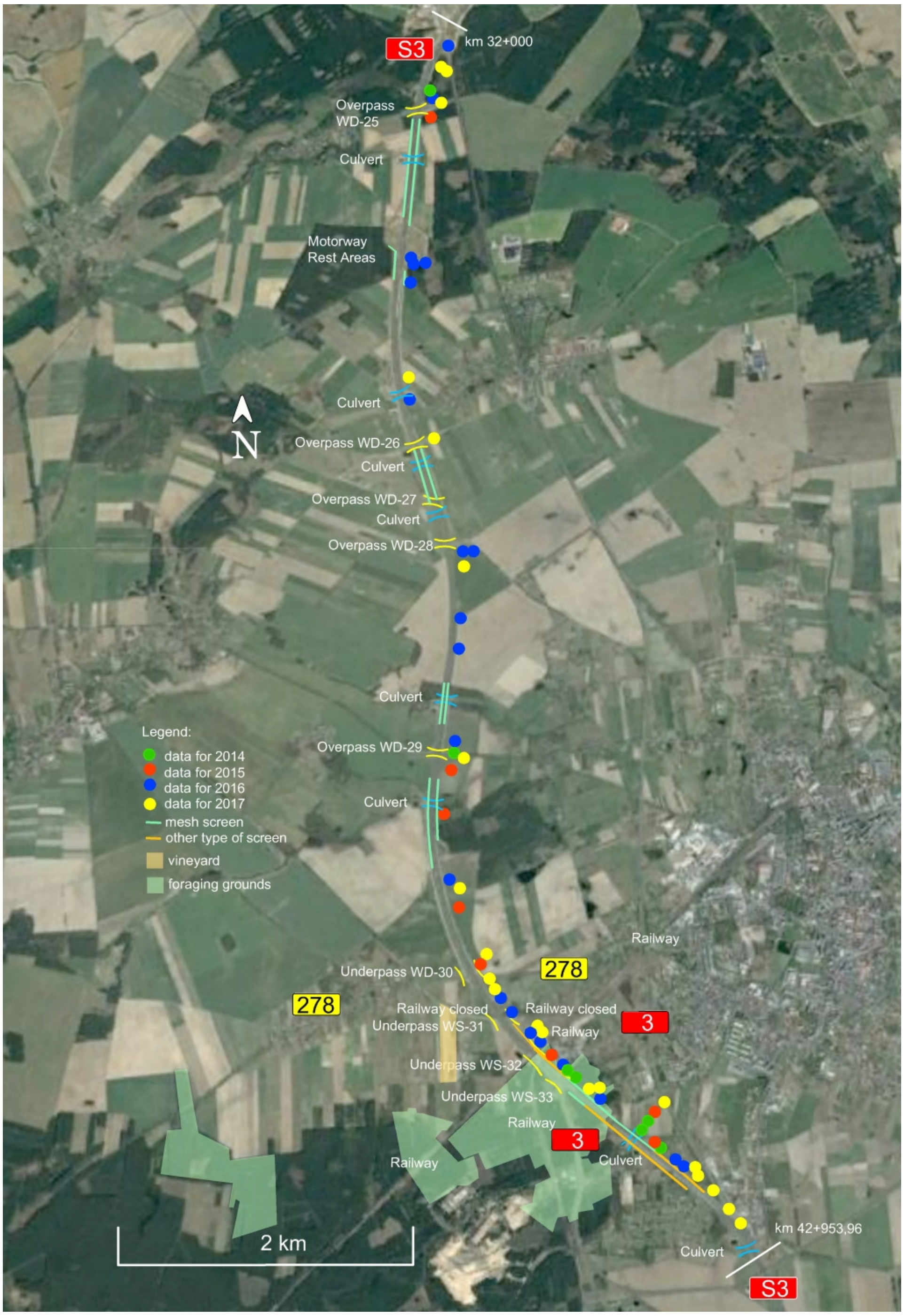


Figure 13. Location of bat carcasses, screens and road overpasses, underpasses and culverts along study section No. 4 of the S3 expressway. (Visualisation by the authors based on the bat mortality data given in the reports [61]).

3.4. Bat Mortality Rates on the Study Sections under Analysis

When evaluating the effectiveness of a mitigating measure used along a bat commuting route, it is customary to use mortality rate data in the relevant analyses. Therefore, in order to evaluate the effectiveness of the screens installed on all three study sections, mortality rates were determined for the road sections without screens, with screens installed on one side of the road and with screens installed on both sides of the road (Figures 14–16). To facilitate the analysis of the presented bat mortality rates distributions on the respective study sections, the lower axis of the graph also shows the length of the analysed road section and the total number of carcasses found on it.

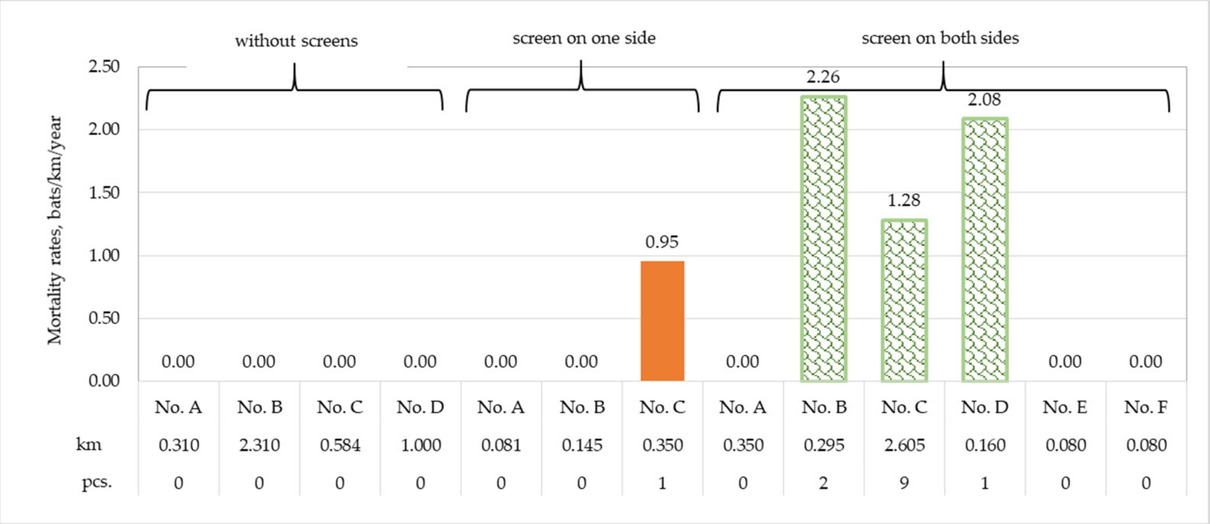


Figure 14. Bat mortality rate distribution across the study section No. 1 of the S3 expressway over the 2014–2016 period (with given length of the road section with or without a given type of screen and the number of carcasses confirmed by monitoring).

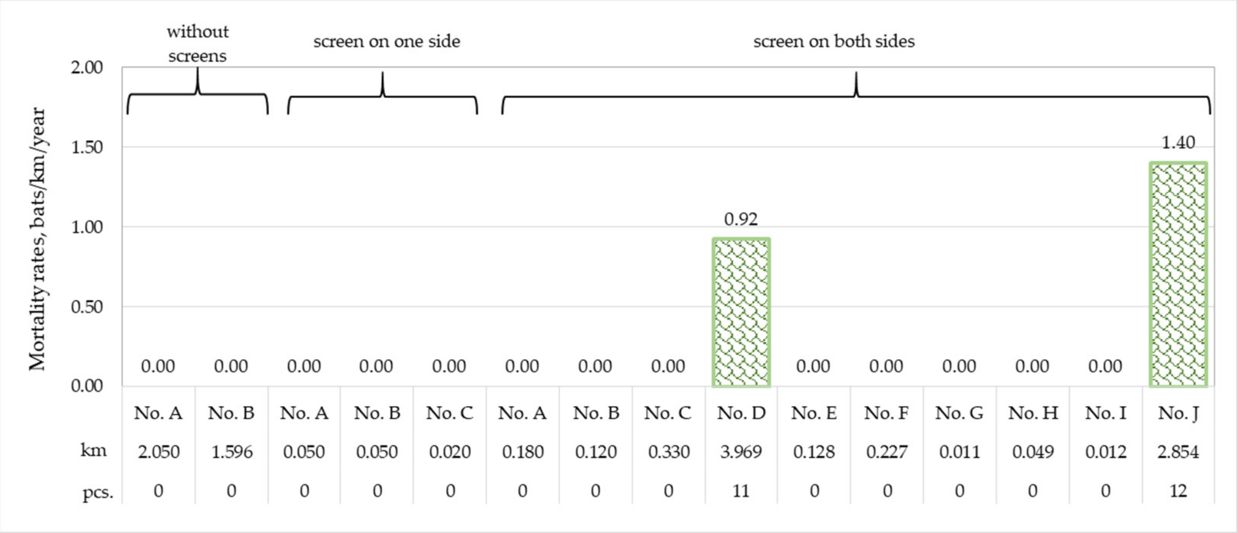


Figure 15. Bat mortality rate distribution across the study section No. 3 of the S3 expressway over the 2014–2016 period (with given length of the road section with or without a given type of screen and the number of bat carcass finds confirmed by monitoring).

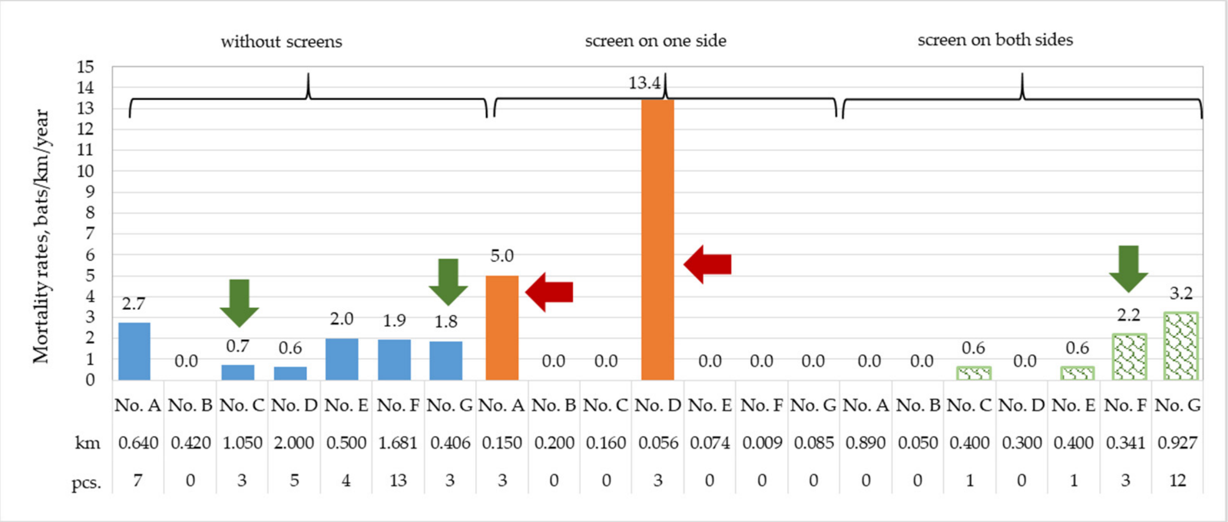


Figure 16. Bat mortality rate distribution across the study section No. 4 of the S3 expressway over the 2014–2017 period (with given length of the road section with or without a given type of screen installed and with the number of bat carcass finds confirmed by monitoring).

A cursory analysis of the graphs shown in Figures 14 and 15 demonstrates that, in the given case, the mortality rate data are not reliable in assessing the effectiveness of the use of mesh screens, as high values of the rate were obtained with one or two bat carcasses found on a short stretch of the road. On the other hand, almost twice as low mortality rates were obtained with 11–12 bat carcasses found on several-kilometres-long stretches of the road with mesh screens installed on both its sides. Study sections No. 1 and 3, shown in Figures 14 and 15, are characterized by long stretches of road with screens installed and with a preliminary cursory analysis, the data could be misread as proving the ineffectiveness of screens as a mitigating measure. However, this would be a very erroneous conclusion, as firstly, there are no confirmed bat commuting and migration routes on study sections No. 1 and 3 on the road stretches without screens, and secondly, Figures 14 and 15 give no additional information about the landscape and land development features in the surroundings of the given section, which perhaps had a more determining effect on bat mortality in the given location.

The data presented in Figure 16 are much more interesting in cognitive terms. Attention is drawn to two sections with screens installed on one of its sides and high mortality rates. In both cases, three bat carcasses were recorded on each of them with almost three times the difference between the lengths of these road sections (Figure 16—marked with a red arrow). The green arrow marks other stretches of the road, on each of which three bat carcasses were also found, but with very different lengths of these stretches.

Figure 17 shows the statistical results of the comparative analyses of bat mortality rates on sections of the road with and without screens, located in study section No. 4 only.

Thus, it is concluded that due to the very varied lengths of the analysed dual carriageway stretches, the mortality rate is of lesser importance and is not a reliable indicator when evaluating the influence of the presence or absence of screens. On the other hand, the mortality rate was found a reliable indicator when comparing longer stretches of the road and their impact on bat mortality (Table 2).

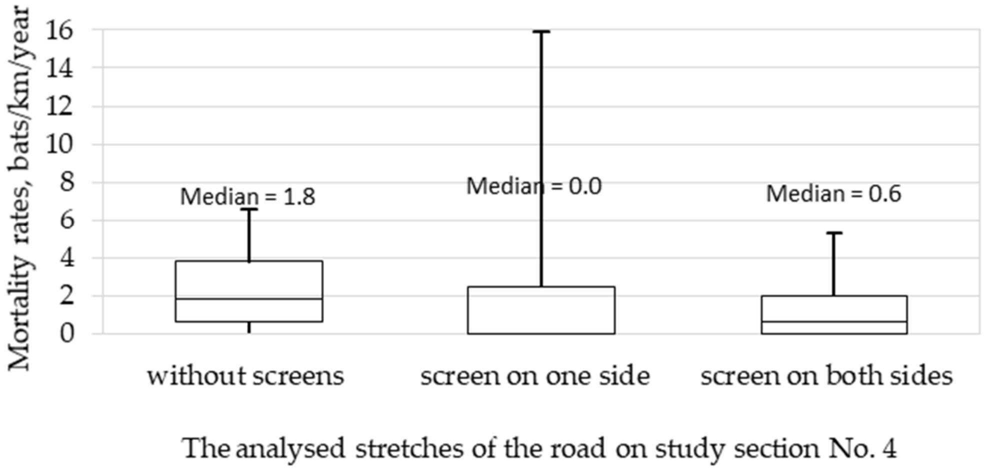


Figure 17. The boxplot of the bat mortality rate on the stretches of the road with various screens installed (data from section No. 4 only). Whiskers represent the minimum and maximum values; the lower and upper edges of the boxes determine the first and third quartiles; and the bold line designates the median value.

Table 2. Summary of basic data on study sections.

Study Section	Road Stretch Characteristics	Years	Number of Bats, Individuals	Length, km	Mortality Rate
No. 1	Without screens	2014–2016	0	4.204	0.00
	With screen on one side		1	0.576	0.58
	With screen on both sides		12	3.570	1.12
	Sum		13	7.460	0.58
No. 3	Without screens	2014–2016	0	3.646	0.00
	With screen on one side		0	0.120	0.00
	With screen on both sides		23	7.880	0.97
	Sum		23	11.646	0.66
No. 4	Without screens	2014–2017	35	6.697	1.31
	With screen on one side		6	0.734	2.04
	With screen on both sides		17	3.308	1.28
	Sum		58	10.739	1.35

Given the above data, the authors of this article argue that there are some additional determinants contributing to bat mortality at the indicated locations, which stands in contrast to the hypothesis that installing mesh screens to raise the flight height of bats above the level of traffic is ineffective. A comparison of bat mortality data on stretches of the road without screens and with screens installed on both sides also does not provide an unequivocal answer on the effectiveness or ineffectiveness of the use of screens, since comparable data on the number of bat carcasses or the length of a given stretch of the road do not include any information on any other possible cause, which probably contributed more to the death of the bats.

4. Discussion

Taking into account the recommendations of the design guidelines [10–20] and the conclusions from the completed research studies [21,22,29,30,36,37,54,56] on the measures to ensure the continuity of linear landscape features along bat commuting and migration routes and on providing natural features to funnel the bats through the areas with severed flight lines, the authors of this article formulated a hypothesis on the importance of the above-mentioned factors, which are probably related to bat mortality.

Considering the difficulty in comparing the impact of individual factors on the number of bat flights at the places where bat commuting routes cross new roads, the authors used the results of the monitoring conducted on the three study sections of the number of bat carcasses found in the selected period, given in the reports [60,61]. When identifying the determinants, the authors of the article proposed using the basic principles of the binary system to determine how many times the interruption of linear landscape features over a length of more than 40 m was confirmed at the location of a bat carcass at a given chainage, and how many times the absence of a natural funnel to guide the bats in flight was confirmed at that location. It was also assumed in the analyses that along the bat commuting route at the place of interrupted continuity of the bat flight line, there should be a natural funnel, for example, in the form of supplementing plantings of designated height installed in the treeline extending up to the screen face or to the wing walls of animal underpasses or culverts as recommended in the publications [11,19,30,56]. Consideration was given to: watercourses, likely constituting existing commuting and migration routes, confirmed in the environmental impact assessment as part of the pre-construction surveys, as well as linear forest gaps or local roads lined with trees, which are also bat commuting and migration routes [10,11,18,21,33]. In the binary system used, one point score was awarded if a probable commuting route was confirmed at a given chainage, while a zero score was awarded if there was no previously confirmed commuting or migration route at the location of the carcass find. Next, if the gap in the continuity of linear landscape features was greater than 30 m, then one point was awarded, as this could contribute to a possible lowering of the height of bat flight and, in consequence, to collisions with a vehicle. Likewise, if there was no natural funnel in place, one point was also awarded at the location where a bat carcass was found. Thus, the first three determinants likely to contribute to lowering the height of bat flight and thus to increasing a bat–vehicle collision risk were assumed.

The next determinants were: a confirmation whether the location of a bat carcass find was situated at a crossing with a transverse road carried over the expressway on an overpass or under the expressway on an underpass. The authors decided that the determinant pertaining to road structures would include also culverts, wildlife overpasses or underpasses, interchanges and, as an exception, also rest areas.

Then, the authors took into account the water environmental conditions, i.e., potential bat foraging grounds, e.g., with confirmed presence of a river, watercourse or retention pond in the vicinity of the location of a bat carcass find. Given the conclusions from the articles [28,29] on the impact of the road lighting system, another determinant was assumed, according to which if a road lighting system was in use near the location of a bat carcass find, it could be a factor contributing to the bat–vehicle collision. The next determinants were related to the structure of the landscape around the expressway, that is, to the confirmation whether in the vicinity of the location of a bat carcass: there was a forest or agricultural land on both sides of the road, or a forest on one side and agricultural land on the other side, and whether there were linear forest gaps or garden allotments or vineyards present which, owing to the mosaic structure of the landscape, could serve as potential bat foraging grounds.

The last determinant adopted by the authors was the confirmation of the presence of the screen either on both sides or only one side of the road or its absence at an identified bat carcass location. Due to the large number of determinants defined, the data from all the study sections were divided into four analytical groups, i.e.: the first body of data related to locations with screens installed at both sides of the road and a road structure present; the second body of data related only to locations where screens were installed at both sides of the road and no road structure was present; the third body of data covering the locations of bat carcass finds where screens were installed only on one side of the road; and the last analytical body of data covering the carcass find locations with no screens installed. Figures 18 and 19 show the results obtained with the use of the above-described binary system for the four aforementioned analytical data categories. For each category, the authors give the total sum of bat carcasses found, and the total number of bat carcasses found at locations with a potential risk of collision (i.e., several dead bats) plus the total number of bat carcasses for locations with only one carcass find.

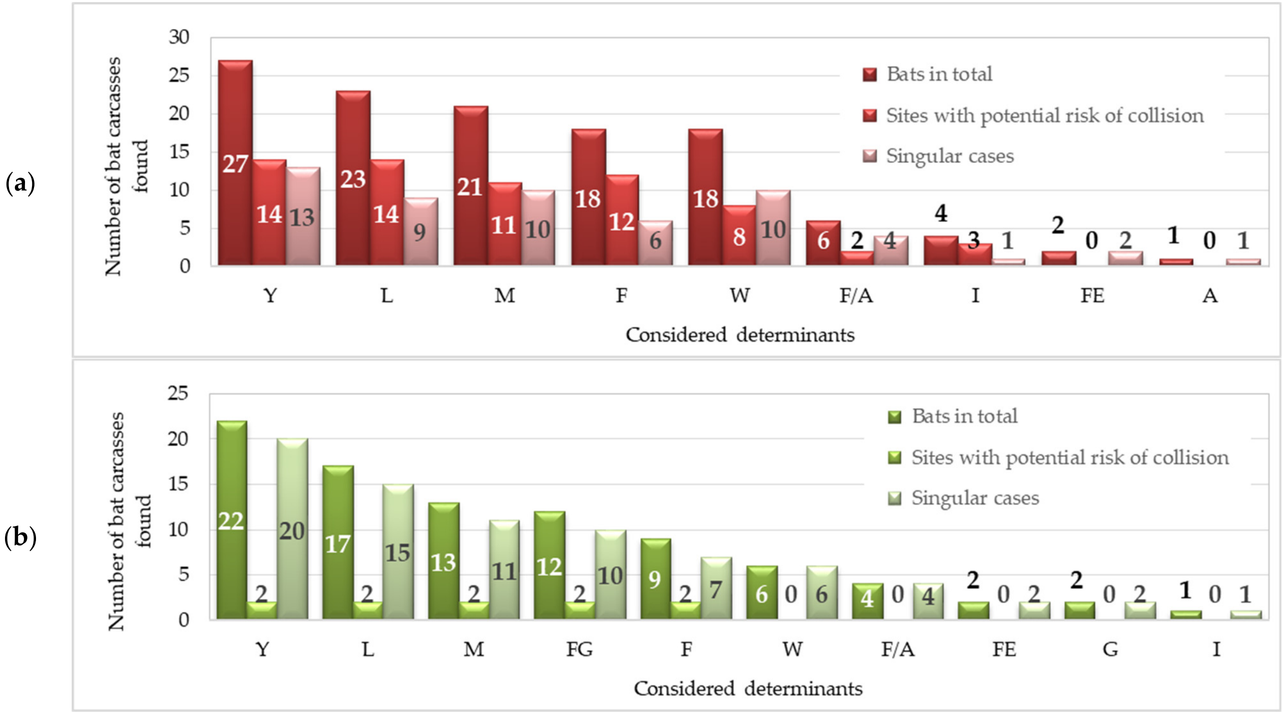


Figure 18. Distribution of determinants on sections with screens installed on both sides of the road: (**a**) 27 sites where bat carcasses were found in the immediate vicinity of a road structure; (**b**) 22 sites where bat carcasses were found outside road structure areas. Determinant designations: Y—lack of natural funnels for bats to fly through, L—distance from the screen to the nearest trees greater than 30 m, M—an existing bat commuting and migration route, either probable or confirmed in pre-construction monitoring, F—forest area on both sides of the road, W—water environmental conditions, F/A—forest land on one side and agricultural land on the other side of the road, I—artificially lit road, FE—forest edge, A—agricultural land on both sides of the road, FG—linear forest gap, G—garden allotments (foraging grounds).

An analysis of the data shown in Figures 18 and 19 indicates that the importance of the selected distribution factors is variable and depends on whether and where the screens are installed on the expressway. To determine possible additional determinants with the screens installed on the expressway, their percentage shares were estimated, as shown in Figure 20. A detailed analysis of the distribution of percentages demonstrated that the most important determinants likely to contribute to lowering the height of bat flight over the road and, in consequence, to creating a potential risk of bat–vehicle collisions are (Figure 20—red line—means over 50%): the lack of natural flight funnels on bat commuting and migration routes, the length of the gap between linear landscape features in close proximity to the road greater than 30 m, the presence of a road structure (overpass, underpass or culvert) without the extension of existing natural plantings along the bat commuting route up to the structure's wing walls, the presence of a linear forest gap without the extension of plantings up to the edge of the screen, the vicinity of a forest with new commuting and migration routes, and water environmental conditions, which provide potential foraging grounds without plantings extending treelines or installed natural funnels for bats to fly through.

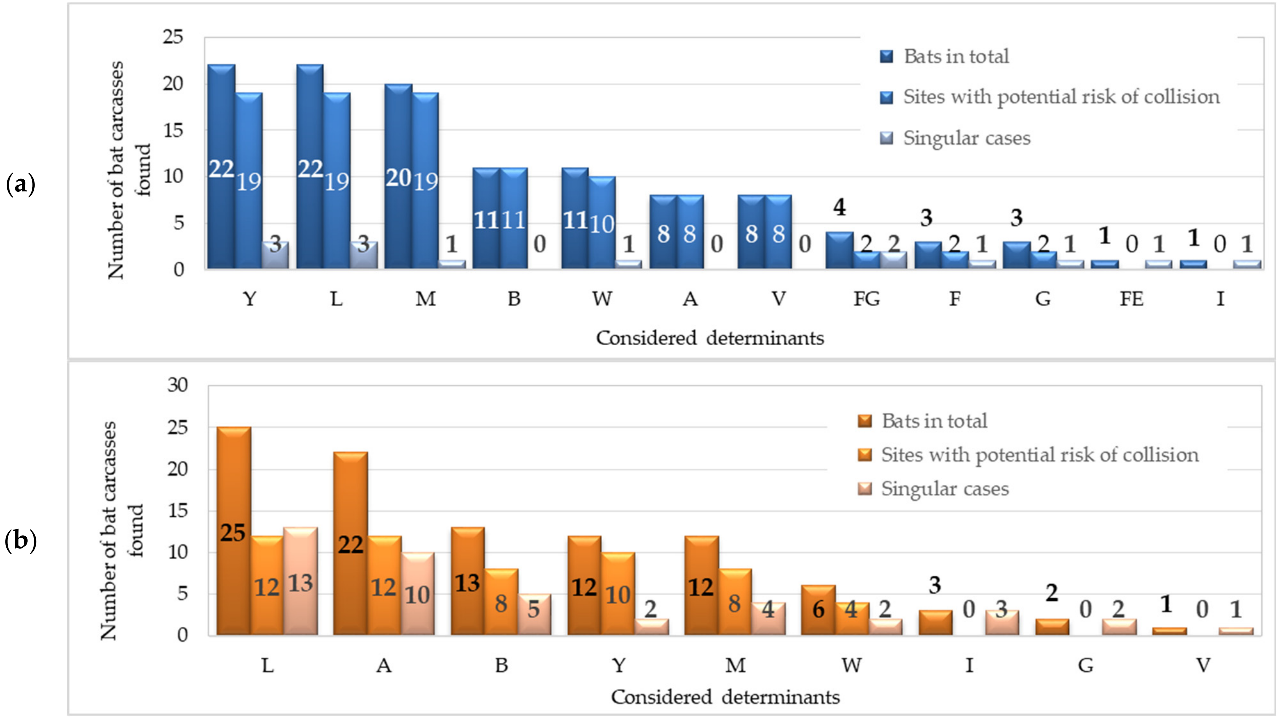


Figure 19. Distribution of determinants: (**a**) 22 locations where a screen was installed on one side of the road; (**b**) 25 locations where no screen was installed. Determinant designations: Y—lack of natural funnels for bats to fly through, L—distance from the screen to the nearest trees greater than 30 m, M—an existing bat commuting and migration route, either probable or confirmed in pre-construction monitoring, B—road structures, W—water environmental conditions, A—agricultural land on both sides of the road, V—vineyard (foraging grounds), FG—linear forest gap, F—forest area on both sides of the road, G—garden allotments (foraging grounds), FE—forest edge, I—artificially lit road, FA—forest area on one side of the road and agricultural land on the other side of the road.

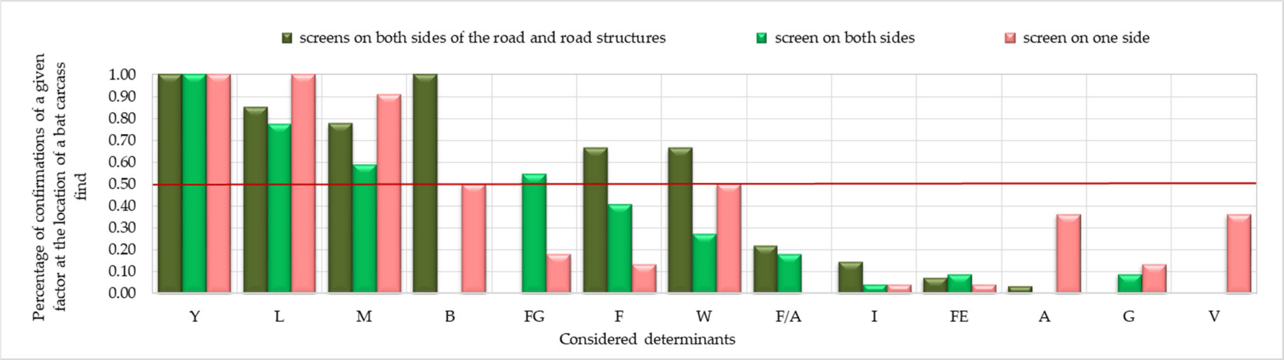


Figure 20. Percentage of locations of bat carcass finds on expressway stretches with screens installed. Determinant designations as in Figures 18 and 19. (Red line—means over 50%).

As a result of an analysis of the locations at which bat carcasses were found on the expressway stretches with no screens installed (Figure 19b), the most significant determinants proved to be: the gap in the linear features of the landscape greater than 30 m, the presence of open agricultural land, and the presence of road structures without natural funnels installed on potential bat commuting and migration routes. According to the conclusions of the guidelines [19], not all bat species have commuting routes located in open agricultural terrain (a treeless uniform agricultural landscape devoid of any structure and including large areas of monoculture crops). In agricultural land, these may be high-flying bats, such as *Nyctalus* or, less frequently, *Eptesicus* or *Pipistrellus*. That is why in most pre-construction studies, less attention is paid to agricultural terrain. On the other hand, if post-construction studies confirm bat mortality in these areas, it is desirable to conduct a bat flight monitoring survey and possibly consider the use of screens or supplementary plantings to raise their flight height.

It should also be mentioned that the determinants indicated in Figures 18–20 were not considered as a single logical tautology, i.e., for example, at a chainage where a screen installed on either one or two sides of the road was used and one determinant finding of a bat carcass was confirmed, only this combination of factors obligatorily meant the significance of the screen, thus confirming the given determinant. Where two or more bats were found, 5–6 or more determinants were recorded, and their combined impact could probably contribute to bats lowering their flight and thus to creating a collision risk situation on the road. For instance, if at a location where 2–3 bat carcasses were found over 3–4 years of research, it was confirmed that: there were screens installed at both sides over a culvert on an existing watercourse, there was a gap in the continuity of linear landscape elements over a length greater than 30 m, and there was no natural funnel for bats to fly through along the potential bat commuting and migration route, then the abovementioned determinants were confirmed.

Given that different bat species demonstrate specific differences in behaviour when in flight [19,49,56,68,77], very different determinants can impact the effectiveness of bat-flight-raising measures. The determined determinants indicate the importance of sustainable interdisciplinary measures undertaken as early as at the stage of pre-construction studies, i.e., identifying bat species and locating their habitats along the planned road, as well as determining the basic design assumptions of the planned sustainable strategy of mitigation of the road's impact to be followed by road builders and landscape architects in close liaison with chiropterologists and design engineers. An analysis of the above-mentioned determinants indicates that it should not be allowed at the stage of the initial civil engineering work (roadwork and overpass, underpass or culvert construction work) for the continuity of the linear landscape elements to be severed for the period of 2 to 3 years of the construction of a new road, which also supports the findings of [10,11,19,20].

According to the conclusions formulated in [6–20,68–70,77], bats remember the commuting and migration routes and need a long time to get used to the new ones. Taking the above into account, planned supplementary plantings in treelines, hedgerows or possible shifting of a commuting route should be analysed as early as at the stage of preparing the pre-construction report [19,20], so that even before, for example, clearing the forest over road right-of-way or starting other preliminary roadworks, care should be taken to preserve the existing commuting and migration routes. The results of bat mortality surveys conducted on the S3 expressway support a thesis that it is also inappropriate to supplement treelines and create natural funnels for bats to fly through also after completion of the work during the 2–3-year period of final improvements while waiting for the planted trees and hedges to mature, which confirms the findings of [10,11,17,19,20].

Yet, another observation from the analysis of the S3 expressway bat mortality rates relates to the matching of the cross-sectional size of, mainly, culverts and underpasses to the needs of bat species active on the commuting and migration routes confirmed in the monitoring surveys conducted as part of the pre-construction studies. As a result, at the planning approval stage, the design engineers would have at hand the exact minimum dimensions of the height and width of a given culvert or underpass. The study reported in [19] presented the aggregate results of dimensions of underpasses and culverts recommended for certain European bat species, based on the data obtained from many research studies [45,77–82]. Based on the confrontation of the road structures built on the S3 expressway and the conclusions from the studies and the reports formulated in [45,76–82], regarding the recommended dimensions of underpasses and culverts on bat commuting and migration routes, the authors believe that the minimum dimensions of culverts should be determined as early as at the stage of preliminary considerations based on the results of pre-construction monitoring surveys, taking into account the species of bats and the heights of their flight that had been confirmed in the monitoring. Additionally, depending on the terrain conditions, the vertical alignment of the designed road, the landscape and development features of the local geography, the possible need for mesh screens, and new supplementary plantings along the treelines or watercourses should be considered before the start of road works, and the lines of natural funnels for bats to fly through should be designated. These preliminary data obtained from chiropterologists regarding the minimum dimensions of the culvert or underpass and the designated lines of natural funnels can be used by design engineers in the sustainable road design process and by landscape architects when working on the development plan and selecting planting species and their heights at the time of planting and when fully grown.

These measures are very much needed to allow bats to fly without changing the altitude and direction of their existing commuting routes, as owing to the use of sustainable mitigation structures better connectivity between the adjacent bat habitats will be achieved. All these sustainable measures are needed at the pre-construction stage, as mitigation measures should be in place before construction begins to allow bats to accept them and get used to them [19,20]. Otherwise, bat populations may decline, and the costly mitigation measures installed may prove ineffective.

Examples of inadequate landscape and land development features at locations where several bat carcasses were found and suggestions for improving this land development are shown in Appendix D. Figure A8 in Appendix D shows a proposal for extending the treeline and the natural funnel installed at culverts. Figure A9 in Appendix D shows a proposal for a natural funnel to be installed before a small wildlife underpass, taking into account the minimum dimensions based on the study results given in [19,20,46,76,77,79–81]. Figure A10 in Appendix D shows a proposal for a natural funnel to be installed before a medium-size underpass, considering the minimum dimensions based on the study results given in [19,46,77]. Figure A11 in Appendix D shows a proposal for a natural funnel to be installed before a large-size underpass, considering the minimum dimensions based on the study results given in [10,19].

One of the purposes of this article was to verify the effectiveness of the use of mesh screens in raising the height of bat flights on commuting and migration routes, and to identify the determinants that attest to this effectiveness. The results presented in Section 3 and in Figures 17–19 attest to the fact that bat carcasses were found at mesh screen locations. That said, a comparison of bat mortality results for road stretches with and without screens demonstrates that if there were no mesh screens in place, bat mortality would likely have been higher. Unfortunately, the above-given determinants indicate that mesh screens alone are not a sufficient measure in raising the flight height of bats and that additional mitigation measures in the form of extended treelines along the commuting and migration routes should be implemented, and that natural funnels for the bats to fly through should be used in areas of forest cleared for the road right-of-way.

The last element analysed in this article was the stretch of the expressway around a rest area. This is a lit area situated on a bat commuting and migration route. For such cases, the French guidelines [10,19] recommend the installation of mesh tunnels. However, in this case, with the existing access and exit roads to and from the rest area, which occupy a large area of land, a tunnel would not be appropriate. In the authors' opinion, the height of flight could have been raised more effectively by providing additional mesh screens, located behind the upper edge of the cut slope, and to improve the rest area with supplementary plantings of 2–4-year-old trees with well-developed crowns and appropriate height, as shown in Appendix D in Figure A11.

5. Conclusions

The analyses carried out as part of this study led to the identification of a few determinants, which in concert with the applied mesh screens, may be appropriately included already at the preliminary design stage to ensure sustainable design. Confirmation of the combined impact of several determinants whose presence was confirmed at the site of potential bat–vehicle collisions is of paramount importance. The most important determinants include:

- Severance of linear landscape elements over a length of more than 30 m;
- No natural funnels installed in the vicinity of underpasses, culvers or overpasses;
- Lack of mesh screens installed in open agricultural terrain along the likely bat commuting and migration routes;
- Screens installed on one side of the expressway on overpasses over local roads and railway tracks, probably serving as bat commuting routes;
- Culverts and underpasses undersized for bat species confirmed in pre-construction monitoring surveys.

The issue of environmental protection has been raised a great deal in sustainable construction in recent decades. The need to address environmental problems is increasingly encountered when constructing new roads, which is especially true of the problem of protecting bat commuting and migration routes. Based on the analysis of the determined determinants, it can be concluded that the interdisciplinary cooperation of chiropterologists, road engineers, design engineers and landscape architects as early as at the stage of pre-construction studies for new dual carriageway road construction projects is very important. An interdisciplinary approach to the project assumptions and further design work can result in more than singular mitigating measures, which may prove ineffective. Interdisciplinary design teams can contribute to designs that take into account multiple factors that significantly increase the effectiveness of sustainable road construction.

Author Contributions: Conceptualization, A.S.; methodology, A.S.; formal analysis, A.S. and D.K.; data curation, A.S. and D.K.; writing—original draft preparation, A.S.; writing—review and editing, A.S. and D.K.; visualization, A.S.; supervision, A.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The details of the monitoring data are available at the GDDiK Branch in Zielona Góra.

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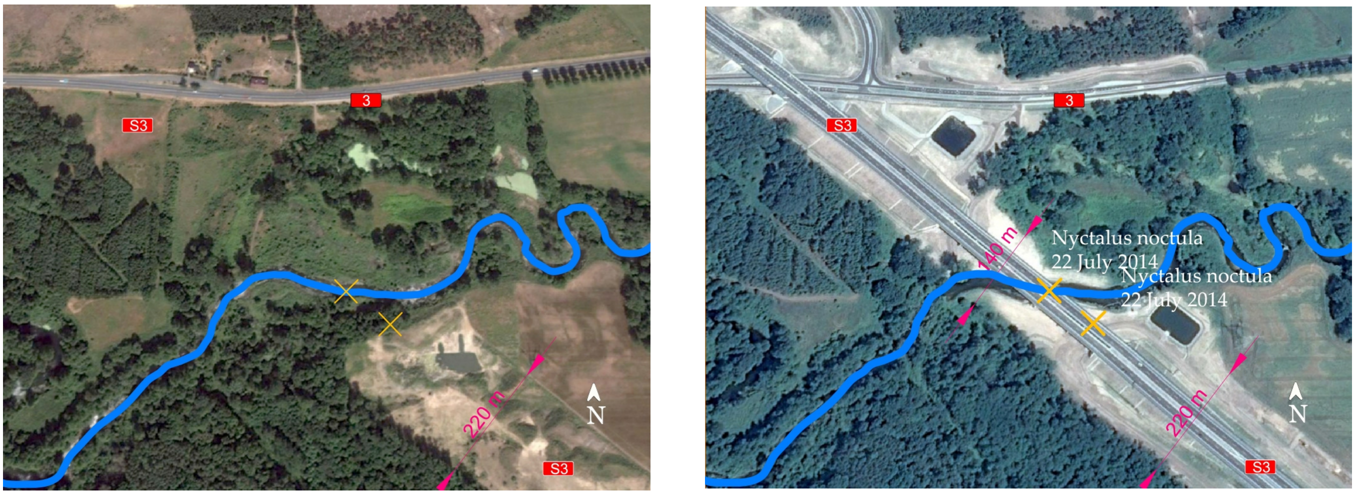
Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Supplementary data—photographic documentation of the collision locations on the study section No. 1.



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

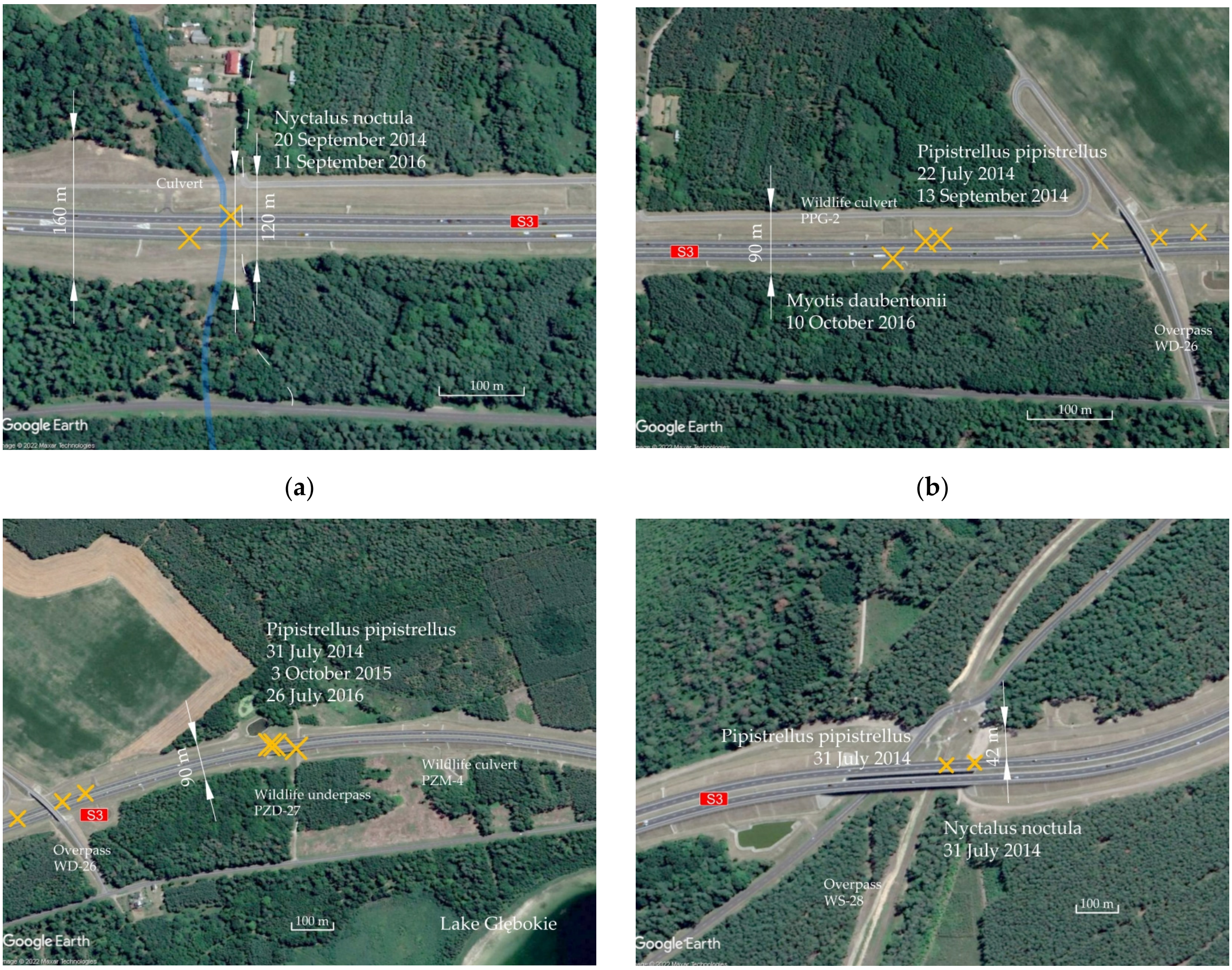
Figure A1. Bat commuting route across the Obra River valley (crosses mark where two *Nyctalus noctula* bat carcasses were found): (**a**) A 2010 view and a 220 m-wide swath of forest cleared for the S3 expressway right-of-way; (**b**) A 2014 view after the road was opened for traffic. (Visualisation by the authors pictured against a satellite image from Google Earth [53].) (blue line—river).

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

Figure A2. Location at which four *Nyctalus noctula* carcasses were found over the 2014–2016 period (cross mark): (**a**) Aerial view of the existing bat commuting route along a local road before the construction of the S3 expressway (celadon line)—status in 2010; (**b**) Aerial view of linear forest gaps, being likely bat commuting routes after the construction of the S3 expressway (orange lines)—status in 2016. (Visualisation by the authors against the background of satellite images from Google Earth [53]).

Appendix B

Supplementary data—photographic documentation of the collision locations on the study section No. 3.



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

(**c**) (**d**)

Figure A3. Landscape and land development features on study section No. 3 in the immediate vicinity of the locations at which several bat carcasses were found over the 2014–2016 period (cross mark), a characteristic lack of a natural fennel for bat to fly through and a ca. 90–160 m swath of forest cleared for the road right-of-way: (**a**) Surroundings of a culvert (H 1.5 m and W 2.5 m) and end of the severed local road, mesh screen, (blue line—stream); (**b**) Surroundings of PPG-2 underpass (H 1.5 m and W 2.5 m), mesh screen, (**c**) Surroundings of PPM-4 underpass (H 1.5 m and W 2.5 m, E-14 screen and mesh screen; (**d**) Surroundings of WS-28 overpass, E-14 screen and mesh screen. (Visualisation by the authors against the background of satellite images from Google Earth [53]).

Appendix C

Supplementary data—photographic documentation of collision locations on study section No. 4.

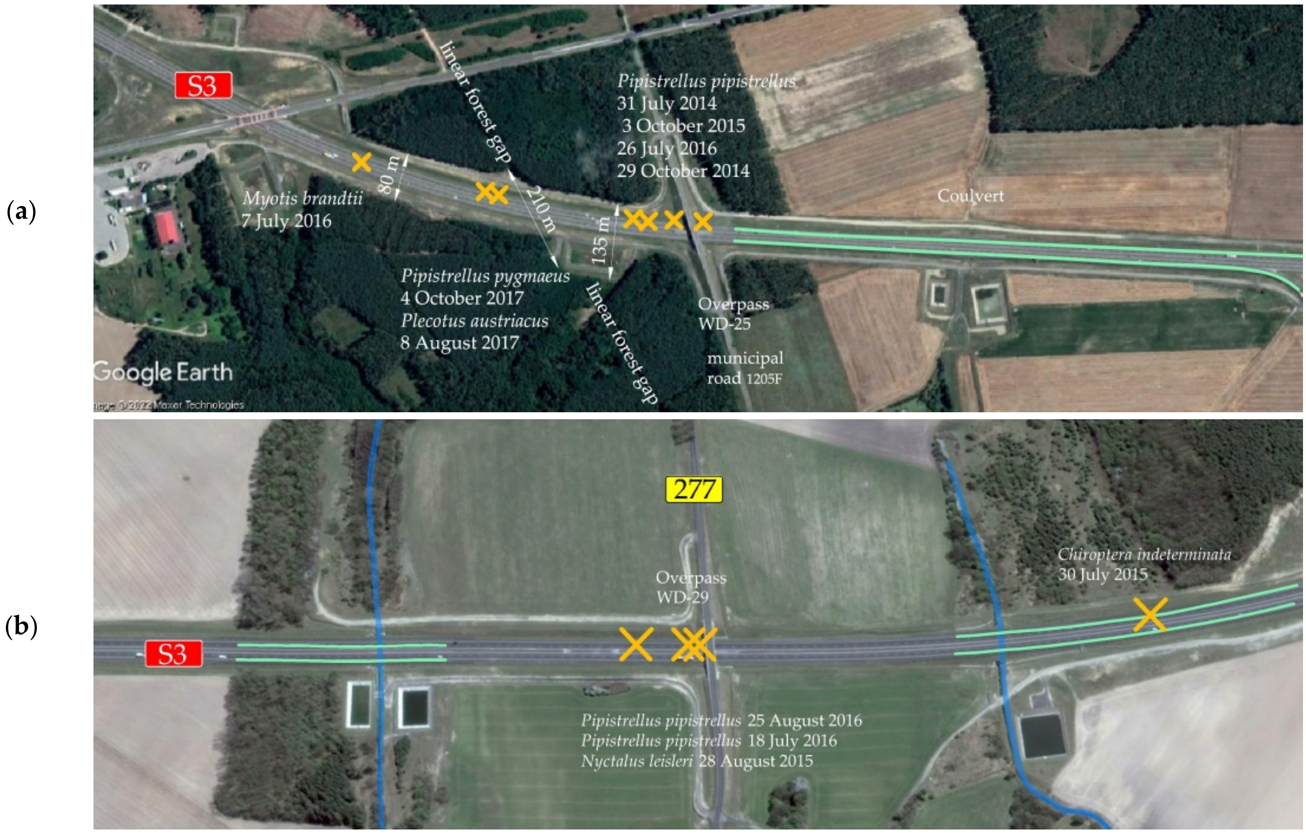


Figure A4. Landscape and land development features on study section No. 3 in the immediate vicinity of the overpasses with no screens installed, and locations at which bat carcasses were found over the 2015–2017 period (cross mark): (**a**) Surroundings of the WD-25 overpass with no screen and no natural funnel for bats to fly through; (**b**) Surroundings of the WD-29 overpass also with no screen or natural funnel for bats to fly through. (Visualisation by the authors against the background of satellite images from Google Earth [53]). (Blue line—stream; green line—mesh screen).

Figure A5. *Cont.*

(b)

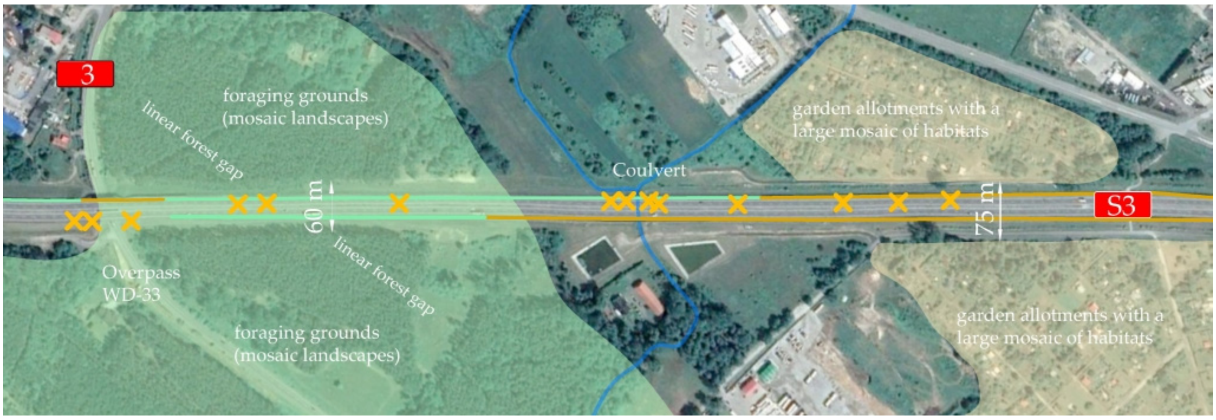
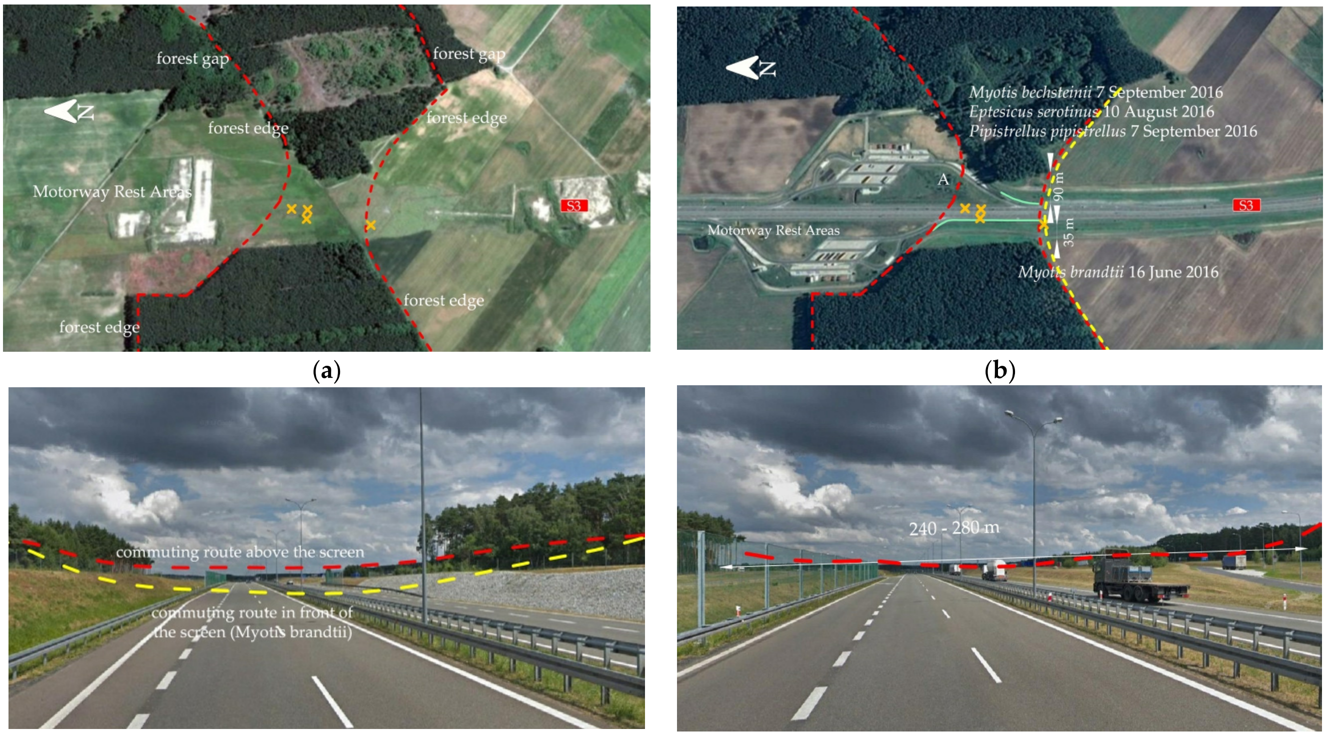


Figure A5. Two stretches of the S3 expressway on study section No. 4 with the largest number of bat carcasses found (locations of carcasses found over the 2014–2017 period are marked with a cross): (**a**) Very varied landscape and land development features with the highest density of overpasses over a short stretch of the S3 expressway, and an absence of screens and natural funnels for bats to fly through; (**b**) Very varied landscape and land development features around the S3 expressway (forest and garden allotments), with mesh screens and noise barriers installed on both sides of the road, double culvert 2 × 2 m. (Visualisation by the authors against the background of satellite images from Google Earth [53]). (Green line—mesh screen, blue line—streams, brown line—noise barrier).



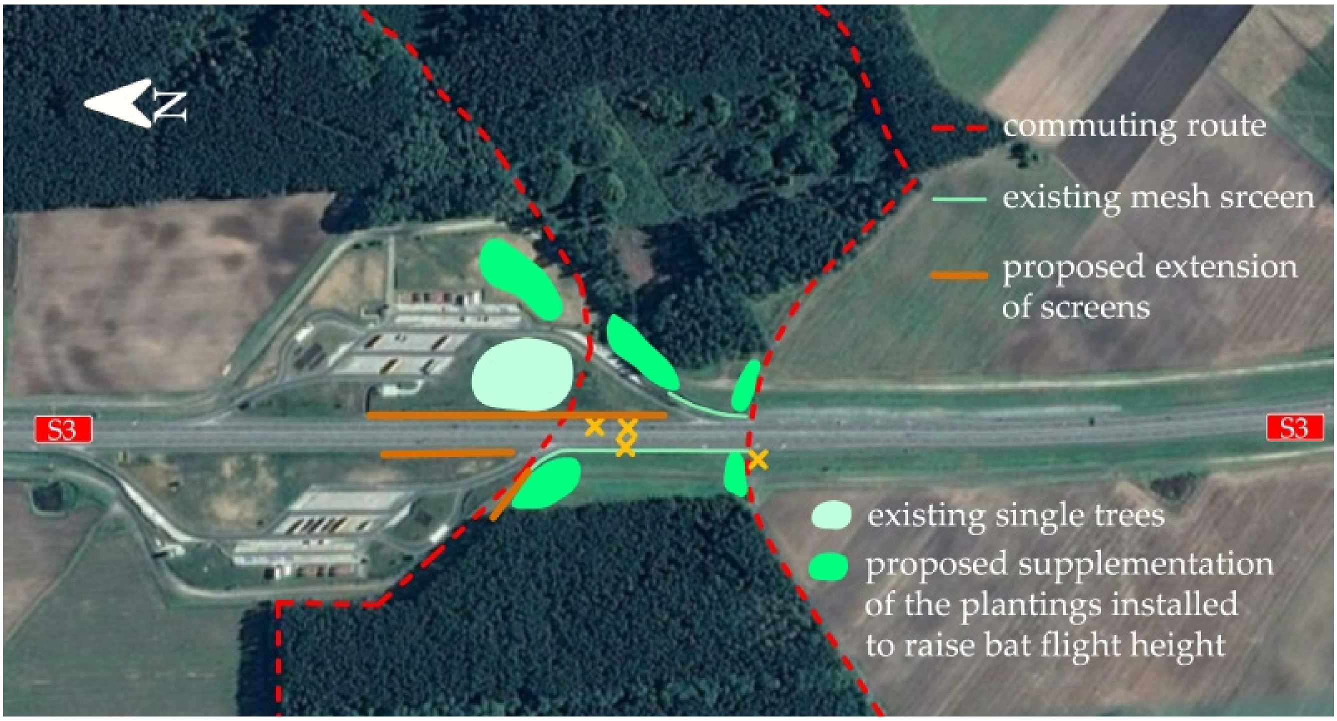
(**a**) (**b**)

(**c**) (**d**)

Figure A6. *Cont.*

(**e**) (**f**)

Figure A6. Landscape and land development features in the rest area: (**a**) Likely bat commuting routes existing up to 2010 and a swath of forest cleared over the width of the right-of-way (red dashed line—commuting route); (**b**) Landscape and land development features in the rest area in 2016 and the mesh screens installed (celadon line) and locations at which bat carcasses were found (orange cross mark), A—single trees on the eastern side; (**c**) View on the access road to the rest area from the south and open terrain, mesh screens visible further in the background, the location where 1 bat carcass was found, the migration line existing so far (red dashed line), likely bat commuting line (yellow dashed line—5 m in front of the screen); (**d**) View on the rest area and the location where 3 bat carcasses were found, single trees visible on the eastern side behind the cut slope, open area over the length of 240–280 m; (**e**) The western side of the rest area and the mesh screen along the forest edge; the mesh screen located 40–55 m from the forest edge, measured from the carriageway edge; (**f**) The eastern side of the rest area, the carriageway edge spaced 125–150 m from the forest edge. (Visualisation by the authors against the background of satellite images from Google Earth [53]).



(**a**)

Figure A7. *Cont.*

(**b**) (**c**)

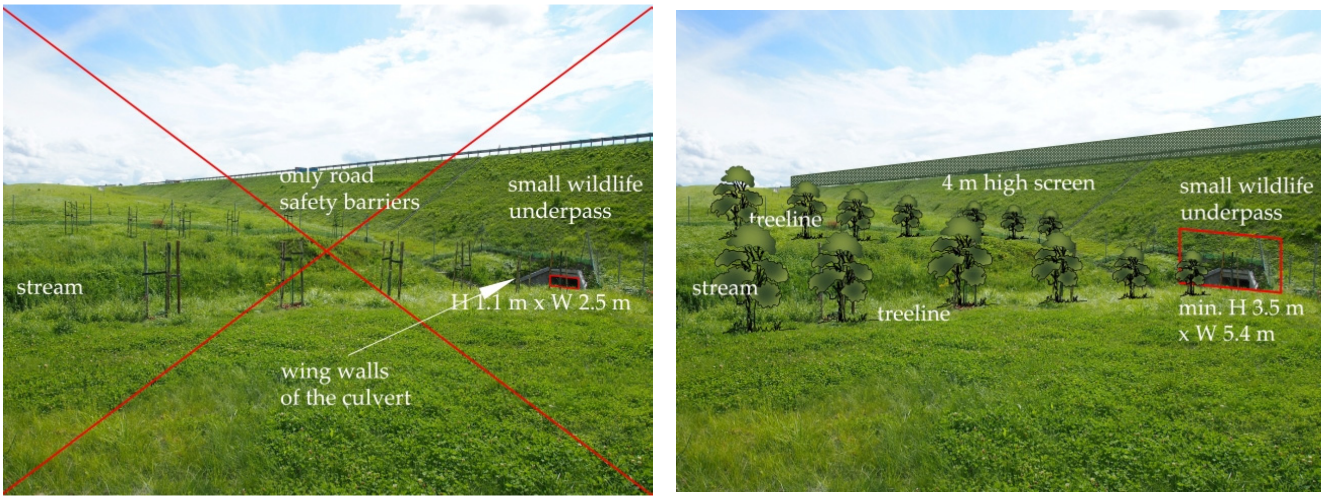
Figure A7. Proposals for the use of additional screens on the cutting slope and supplementary plantings to raise bat flight above 4 m over the rest area site: (**a**) Plan; (**b**) Western side; (**c**) Eastern side. (Visualisation by the authors against the background of satellite images from Google Earth [53]).

Appendix D

Examples of proposed natural funnels for bats to fly through.

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

Figure A8. Landscape and land development features in the surroundings of a culvert: (**a**) Poor land development around the stream, one-year-old tree seedlings planted after the road was open for traffic, inadequate for the altitude of bat flight and the inside clearance distances of the culvert; (**b**) Proposed mature tree plantings adequate for the height of bat flight and the inside clearance distances of the culvert, directed straight at the wing walls of the culvert.



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

Figure A9. Landscape and land development features in the surroundings of a small underpass: (**a**) Poor land development around the stream, one-year-old tree seedlings planted after the road was open for traffic, inadequate for the altitude of bat flight and the inside clearance distances of the underpass; (**b**) Proposed installation of a mesh screen and planting of mature trees adequate for the height of bat flight and the inside clearance distances of the wildlife underpass, directed straight at the wing walls, larger cross-section of the underpass.

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

Figure A10. Landscape and land development features in the surroundings of a medium underpass: (**a**) Poor land development around a stream, one-year-old tree seedlings planted after the road was open for traffic, inadequate for the altitude of bat flight and the inside clearance distances of the underpass, absence of a screen raising the height of bat flight; (**b**) Proposed installation of a mesh screen and planting of mature trees adequate for the height of bat flight and the inside clearance distances of the wildlife underpass, directed straight at the wing walls of the underpass.

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

Figure A11. Landscape and land development features in the surroundings of a large underpass: (**a**) Poor land development around a stream, one-year-old tree seedlings planted after the road was open for traffic, inadequate for the altitude of bat flight and the inside clearance distances of the underpass, absence of a screen raising the height of bat flight; (**b**) Proposed installation of a mesh screen and planting of mature trees adequate for the height of bat flight and the inside clearance distances of the wildlife underpass.

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