Green Bridges and Their Migration Potential

Jaroslav Žák, Aleš Florian

Abstract**—**Green bridges enable wildlife to pass through linear structures, especially freeways. The term migration potential is used to quantify their functionality. The proposed methodology for determining migration potential eliminates the mathematical, systematic and ecological inaccuracies of previous methodologies and provides a reliable tool for designers and environmentalists. The methodology is suited especially to medium-sized and large mammals, is mathematically correct, and its correspondence with reality was tested by monitoring existing green bridges.

Keywords**—**Green bridges, migration potential, partial probabilities, wildlife migration.

I. Introduction

GREEN bridges (wildlife crossings, overpasses) and underpasses are known as migration objects (having migration profiles). They increase the probability for wildlife to pass through linear traffic structures (so-called wildlife permeability). To quantify the probability of a migration object's functionality, the quantity known as migration potential is used. The paper describes the methodology currently used in the Czech Republic and elsewhere [1], the methodology newly proposed by the authors, and a comparison between the two. Both methodologies may be utilized for medium-sized and large mammals.

Section II describes the existing methodology for determining migration potential according to the approved technical conditions of the Ministry of Transport of Czech Republic, and it also highlights their mathematical and ecological shortcomings.

Section III describes the newly proposed methodology for quantifying migration potential, which eliminates the deficiencies of the aforementioned methodology. It describes with mathematical precision and ecological credibility the probability of a migration object's functionality.

Section IV contains a comparison of the two methodologies at two already implemented freeway bridges that are monitored, among other methods, by a camera system.

II. Existing Methodology

Individual animal species are grouped into basic categories according to their similar characteristics relating to migration (see Table I). Their (sometimes considerably) different behavior within categories is not taken into consideration when determining migration potential (for details see [1]).

Migration potential MP is defined as the probability of the functionality of the migration profile. MP is calculated as the product of its two components: the ecological migration potential MPE and the technical migration potential MPT.

$$MP = MPE \times MPT \tag{1}$$

The authors [1] correctly state that the resulting probability of two independent phenomena is equal to the product of the individual probabilities and it lies within a closed interval of zero to one.

A. Ecological Migration Potential MPE

MPE is defined by two components: the importance of the migration route MPEA and by the disturbing influences in the surrounding environments MPEB. Already here a clear inconsistency can be observed. The stability and regularity of using a migration route is itself indisputably impacted by disturbing influences. One cannot speak of great migration pressure where there are strong disturbing influences.

However, the fact that there are disturbing influences prior to initiating road construction is especially problematic. MPE thus expresses the probability of the migration route being used before the road is constructed. The result is therefore not the real migration potential after the migration profile has been implemented, but rather a "hypothetical" migration potential corresponding to migration without a constructed road. The situation after completion of the construction is often different, and disturbing influences may be more pronounced and can even increase in the future. Thus the calculated migration potential is again a hypothetical figure related to the state prior to initiating construction (the so-called zero variant) and not to the probability of the migration profile's functionality in the future. When deciding on the type and costliness of a migration profile, however, it is necessary to know the probability of its functionality after completion (of the road and of the migration object) and after decades of operation, not that in the zero variant.

The authors [1] present their calculation of MPE as the geometric mean of the two components

$$MPE = (MPEA \times MPEB)^{1/2} \tag{2}$$

They do explain the use of the geometric mean by the fact that if one of the components is zero, the result will also be zero (a nonfunctional state). This requirement for the selection of a function is, of course, correct; however, it can also be satisfied by a number of other functions.

In certain cases, very skewed results are obtained due to this choice. For example, if the following are entered into (2)

$$MPEA = 0.95 \text{ and } MPEB = 0.05 \tag{3}$$

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(i.e., exceptionally strong disturbing influences practically preventing migration), we obtain

$$MPE = (0.95 \times 0.05)^{1/2} = 0.22 \quad (4)$$

which in combination with an excellent MPT = 1.0 gives the resulting migration potential as MP = 0.22.

TABLE I
DIVISION OF SELECTED WILD MAMMALS INTO CATEGORIES

Category	Description	Examples of species
A	Large mammals	Red deer, lynx, brown bear, gray wolf, moose
B	Medium-sized mammals, ungulates	Roe deer, wild boar, mouflon
C	Medium-sized mammals, predators	Red fox, European badger, small predators of the weasel family

In other words, in a situation of extremely strong disturbing influences, a below-average but nevertheless usable functionality is obtained, even in the event that the migration profile is practically nonfunctional. This is precisely the result of the ill-considered use of the square root in (2), which augments the result in case of very small MPEA and/or MPEB values. More specific

$$(1.0 \times 0.01)^{1/2} = 0.1 \quad (5)$$

and

$$(1.0 \times 0.0001)^{1/2} = 0.01 \quad (6)$$

If the MPEA and MPEB values approach 1, the unreasonableness of using the square root is not so crucial, for example

$$(1.0 \times 0.95)^{1/2} = 0.97 \quad (7)$$

which is quite a "reasonable" result within the expected range.

Paradoxically, it is possible to determine a qualified estimate of MPE directly using a table, which will in most cases lead to more realistic numbers. In general, the best possibility is a route of exceptional importance without disturbing influences. Meanwhile, there is no variant in the form of an exceptionally important route with crucial disturbing influences. Understandably, in the so-called zero variant with crucial disturbing influences, the route cannot be both important and vice versa. Nevertheless, is it really possible that there cannot be a situation in which an originally important route is affected by crucial disturbing influences after the road is completed? Imagine a pristine, large meadow with an exceptionally important migratory route and no disturbing influences. After a road is opened, a large truck stop with an all-night bar and casino will be built at the point where the road intersects the migration. The obvious disturbing influences will produce MPEB = 0.05 in the future. What will MPE be? By the existing methodology, it appears that (according to the zero variant) MPE = 1.0.

This clearly indicates that it is necessary to separate the importance of the route in the zero variant and the probability of future disturbing influences. Understandably, this does not in any way affect the very correct requirement stated in [1] "to pay exceptional attention to and ensure… the protection of already constructed migration structures". Nevertheless, it is essential to be attentive so that these influences will be both mathematically and factually included correctly into the calculation of migration potential.

B. Technical Migration Potential MPT

MPT is given by the geometric mean of two components: the potential of the technical solution MPTA and the potential for eliminating the disturbing impacts of the infrastructure in operation MPTB, i.e.

$$MPT = (MPTA \times MPTB)^{1/2} \quad (8)$$

In the cases of underpasses, MPTA is defined as:

$$MPTA = (MPTA1 \times MPTA2 \times MPTA3)^{1/3} \quad (9)$$

where MPTA1, MPTA2 and MPTA3 are determined from different nomograms [1] for each category of fauna.

For overpasses, MPTA is defined as

$$MPTA = (MPTA4 \times MPTA5)^{1/2} \quad (10)$$

where MPTA4 and MPTA5 are also determined from different nomograms [1] for each category of fauna. This implies that MPT and overall MP are established individually for each category of fauna.

The use of geometric means nevertheless makes even less sense here that in determining MPE. In particular, use of the cube root in the calculation of MPTA for underpasses increases very small (almost zero) numbers even more markedly than does the square root. To illustrate

$$(1.0 \times 1.0 \times 0.0001)^{1/3} = 0.05 \quad (11)$$

The use of nomograms [1], if they are based on a sufficient number of calibrating samples, does not have to be bad. Unfortunately, it is neither defined nor explained what exactly MPTA and MPTB values actually mean, whether they are probabilities or some kind of empirical coefficients.

For MPTA4 component calculation, the index C is used [1]. It is defined as the ratio of the maximum width b and length l (see Fig. 1).

$$C = b/l \quad (12)$$

Minimum width a (see Fig. 1) thus does not affect index C at all, and identical index C values –and thereby identical MP values – are obtained for various a/b ratios. This does not at all reflect the fact that for large minimum widths of overpasses (e.g., equal to or greater than 100m), it is not necessary to propose large maximum width b.

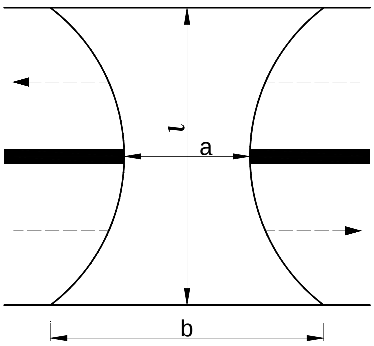

Fig. 1 Overpass dimensions

The authors [1] also claim that "the use of geometric means ensures that in a case when one of the numbers falls below the threshold of acceptability the entire bridge construction is designated as unacceptable." However, this only applies for "unacceptability" equal to zero. If, for example MPTA1 = 0.03 (practically unacceptable), MPTA2 = 1.0 and MPTA3 = 1.0, then we obtain

$$MPTA = (0.03 \times 1 \times 1)^{1/3} = 0.31 \quad (13)$$

which decidedly is not an unacceptable value for a migration structure.

C. Summary of the Existing Methodology

The methodology [1] can provide acceptable results, especially if partial components of MP approach 1. The use of geometric means is neither explained nor justified, and it produces unusable results for numbers lower than 0.1. It does not reflect the probability of disturbing influences in the future. A single value representing disturbing influences for all categories of fauna also does not correspond to reality, as the various categories (and sometimes even individual species) respond differently to identical disturbing stimuli. The minimum profile width has no influence on index C. This does not reflect the fact that it is not necessary to design large ramps for large widths of overpasses. The use of geometric means does not guarantee that in the event one of the numbers falls below the acceptable threshold the entire construction of the migration structure will be designated as unacceptable. The definition of MP as a probability implies that it cannot be larger than 1, which the algorithm of the current methodology does not ensure.

III. Proposed Methodology

Migration potential P is also calculated as a product of two components: the ecological migration potential $P_e$and the technical migration potential P_t

$$P = P_e \times P_t \quad (14)$$

Thus far, the only difference is in the notation used. We do not question the fact that the resulting probability of two independent phenomena is equal to the product of the individual probabilities and lies within a closed interval between 0 and 1. In the case of a technically ideal solution (P_t = 1), P_e is equal to the resulting migration potential P, while P_t is equal to the resulting migration potential P in the case of an exceptionally important migration route without disturbing influences (P_e = 1).

However, P_e expresses the probability of the migration route being used after road construction. The result is therefore the probability of future functionality, which means real migration potential after implementation of the migration structure.

A. Ecological Migration Potential P_e

Ecological migration potential P_e is defined as the product of the probability of the importance of the migration route P_{ec} and the complement of the probability of future disturbing influences in the environment P_{er}. As these are two independent phenomena, the resulting probability is the product of the individual probabilities, and therefore

$$P_e = P_{ec} \times P_{er} \quad (15)$$

Use of the product ensures (as does the geometric mean in [1]) that in an event the properties of one component will be limiting and unacceptable for migrations, the resulting value P_e will be zero (i.e. it will also indicate a nonfunctional state). Moreover, disturbing influences can only decrease (or maintain for P_{er} = 1) the probability of the importance of the migration route, not increase it.

P_{ec} = P_e in a case of zero disturbing influences (P_{er} = 1) while P_{er} = P_e in a case of an exceptionally important migration route (P_{ec} = 1). In a case of exceptionally strong disturbing influences, P_{er} = 0. When there are absolutely no disturbing influences, P_{er} = 1.

To demonstrate, if according to the existing methodology MPEA = 0.3 and MPEB = 0.7, then we obtain [1]

$$MPE = (0.3 \times 0.7)^{1/2} = 0.46 \quad (16)$$

which means that disturbing influences increased the probability of migrations.

According to the proposed methodology, however, P_{ec} = 0.3 and P_{er} = 0.7 and thus

$$P_e = 0.3 \times 0.7 = 0.21 \quad (17)$$

This means that disturbing influences decreased the probability of migrations (as should be expected).

It is necessary to define individually the probabilities of future disturbing influences in the environment for each category of fauna or for each species according to its ethological characteristics, which is not the subject of this article.

B. Technical Migration Potential P_t

Technical migration potential P_t is defined by two factors: the probability for functionality of the technical solution P_{tt} and the complement of the probability of disturbing influences from the infrastructure's operation P_{tr}. As these are again two independent phenomena, the resulting probability is the product of the individual probabilities, and therefore

$$P_t = P_{tt} \times P_{tr} \tag{18}$$

P_{tt} is the probability that the dimensions of the migration profile will not affect the functionality of the migration profile. The ideal state is P_{tt}= 1, in which case the parameters of the migration profile have no impact on migration. P_{tt} = 0 means that the parameters of the migration profile do not allow any migration.

P_{tr} is the probability that disturbing influences from the infrastructure's operation will not affect the functionality of the migration profile. P_{tr}= 1 is the ideal state, while P_{tr} = 0 means that disturbing influences wholly prevent migration. The probability of disturbing influences from the infrastructure's operation is again defined individually for each category of fauna.

For underpasses, P_{tt} is defined as

$$P_{tt} = P_w \times P_h \times P_{whl} \tag{19}$$

where P_w, P_h and P_{whl}, represent partial probabilities. They are determined from functional dependencies (as described in Section III *C*) that differ for each category of fauna.

For overpasses, P_{tt} is defined as

$$P_{tt} = P_a \times P_b \times P_{al} \tag{20}$$

where P_a, P_b and P_{al} represent partial probabilities too. They are defined from functional dependencies (again described in subsection III.C) that differ for each category of fauna.

C. Partial Probabilities

The functions (partial probabilities) describing dependencies of technical parameters on the probability for the functionality of the technical solution (overpass or underpass) were derived on the basis of analyzing large amounts of the records from camera systems and camera traps, long-term monitoring, personal experience and credible information from the literature (see [2]-[5]), as well as from personal consultations.

For easier use, the dependencies were formulated as continuous functions in two variants. The first variant (exact variant) models the real dependencies as precisely as possible and is suitable for precise analysis and examination of nearly nonfunctional parameters. The second variant (practical variant) is suitable for practical use in evaluating proposed or existing migration profiles.

For the exact variant, the function P_y corresponding to a gamma distribution function was selected

$$P_y = \int_0^x \frac{u^{\alpha-1} e^{-u/\beta}}{\beta^\alpha \Gamma_{(\alpha)}} du \tag{21}$$

where y is the relevant technical parameter – width w of the underpass, height h of the underpass, whl (ratio of the area S and length l of the underpass), width b of the overpass, the minimum width a of the overpass, and al (ratio of the minimum width a and length l of the overpass); x represents possible positive values of the relevant technical parameter; P is the partial probability; Γ is gamma function, and α and β are constants greater than zero defined for each category of fauna and the relevant technical parameter.

The practical variant uses the function

$$P_y = 1 - e^{-\gamma(x-\delta)} \tag{22}$$

where γ and δ are constants defined for each category of fauna and the relevant technical parameter.

1. Underpasses

The function P_w defines the influence of the underpass width on the probability of the technical solution's functionality. The constants α, ß, γ and δ for the individual categories of fauna are shown in Table II.

Graphic representation of the exact and practical variants of the function P_w for the category roe deer and their comparison with nomograms according to [1] are presented in Fig. 2.

The function P_h defines the influence of the underpass height on the probability of the technical solution's functionality. The constants α, ß, γ and δ for the individual categories of fauna are shown in Table III.

Graphic representation of the exact and practical variants of the function P_h for the category roe deer and their comparison with nomograms according to [1] are presented in Fig. 3.

The function P_{whl} defines the influence of index I_u (ratio of the area S and length l of the underpass) on the probability of the technical solution's functionality. For a rectangular underpass

$$I_u = {}^{S}/_{l} = {}^{wh}/_{l} \tag{23}$$

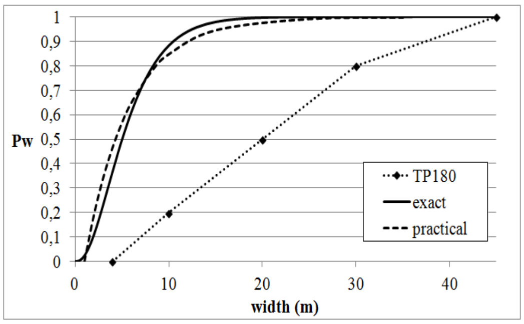

Fig. 2 Category roe deer – dependence of Pw on width of the underpass (m)

TABLE II
P_w: THE CONSTANTS α, β, γ AND δ FOR THE INDIVIDUAL CATEGORIES OF FAUNA

Category	α	β	γ	δ
Red deer	2.1	4.0	0.11	1.9
Roe deer	2.3	5.0	0.12	2.7
Red fox	2.6	6.5	0.16	3.3

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It is important here to emphasize the fact that the area S is not an ideal value, as theoretically there can be situations when, even with a relatively large area, the underpass will not be usable for mammals due to one of the parameters (height or width). In practice, especially very wide underpasses with a low pass-through height can be considered. These situations are eliminated, however, by the computation of the function P_h, which in the case of a low underpass height (according to category) gives very low (in the case of exact variant) or zero (in the case of practical variant) probability of its functionality for the target species.

2. Overpasses

The function P_a defines the influence of the minimum overpass width on the probability of the technical solution's functionality. The constants α, ß, γ and δ for the individual categories of fauna are shown in Table IV.

Graphic representation of the exact and practical variants of the function P_a for the category roe deer and their comparison with nomograms according to [1] are presented in Fig. 4.The function P_b defines the influence of the maximum overpass width (ramp) of the on the probability of the δfor the individual categories of fauna are shown in Table V.

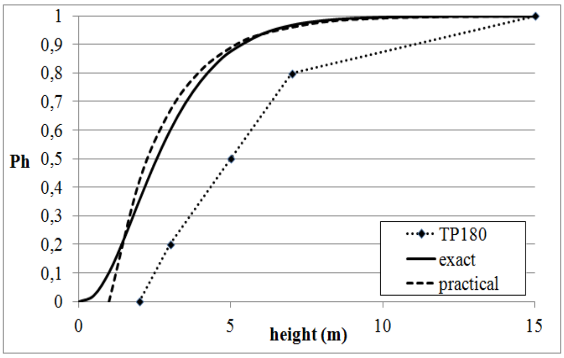

Fig. 3 Category roe deer – dependence of Ph on width of the underpass (m)

Graphic representation of the exact and practical variants of the function P_b for the roe deer is presented in Fig. 5.

The function P_{al} defines the influence of index I_o (ratio of minimum width a and length l of the overpass) on the probability of the technical solution's functionality

$$I_0 = {}^{a}/_{l} \tag{24}$$

TABLE III
P_H: THE CONSTANTS α, β, γ AND δ FOR THE INDIVIDUAL CATEGORIES OF FAUNA

Category	α	β	γ	δ
Red deer	2.1	4.0	0.11	1.9
Roe deer	2.3	5.0	0.12	2.7
Red fox	2.6	6.5	0.16	3.3

D.Summary of the Proposed Methodology

The proposed methodology provides objective results for any values of the partial parameters. The probability of disturbing influences in the future is taken into consideration. The probability of disturbing influences from the infrastructure's operation is defined individually for each category of fauna, as there is the probability of future disturbing influences in the surrounding environs. Total migration potential is always within a closed interval between 0 and 1.

IV. Comparison of Existing and Proposed Methodologies

The two described methodologies were compared when calculating the migration potential of two freeway bridges already completed on the Czech Republic's D1 freeway. Both bridges have been monitored using a camera system for along time.

A. Freeway Bridge SO 204

The bridge SO 204 on the section D4704 of the D1 freeway crosses Hlásenec stream and a local class III road. Good conditions for migration were originally assumed due to the technically suitable solution and the stream. The results of monitoring however indicate zero migrations of category B animals. Apparently, the influences of a nearby brickworks and a road create a negative effect.

Technical parameters of the underpass are: width 27m, height 5m, length 38m. The calculations according to both methodologies gave us the following results. The migration potential according to the current methodology MP = 0.21 is distorted by use of the root with a route of small importance.

TABLE IV
P_A: THE CONSTANTS α, β, γ AND δ FOR THE INDIVIDUAL CATEGORIES OF FAUNA

Category	α	β	γ	δ
Red deer	1.3	6.5	0.04	2.1
Roe deer	2.4	5.1	0.11	3.1
Red fox	4.9	3.3	0.12	3.2

The migration potential according to the proposed methodology P = 0.06 is in accordance with reality. According to the methodology currently in use, MP is markedly higher than that determined by the proposed methodology.

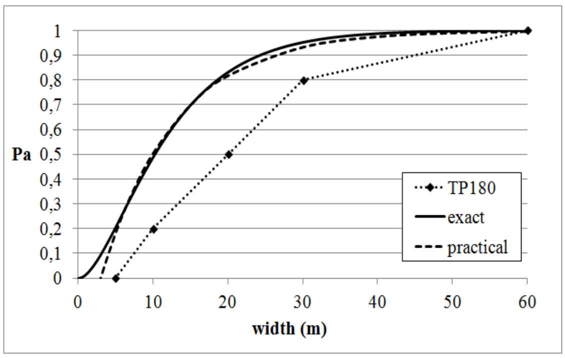

Fig. 4 Category roe deer – dependence of Pa on the minimum width of the overpass (m)

B. Freeway Bridge SO 208

The bridge SO 208 on the section D4704 of the D1 freeway crosses Žabník stream in the vicinity of an originally proposed overpass. This site is considered the most probable migration route between the Beskydy and the Jeseníky Mountains. The results of monitoring so far indicate a 30% probability for functionality of the migration structure for category B animals. Adjustments that should increase the functionality have been proposed.

Technical parameters of the underpass are: width 11m, height 3m, length 35m. The calculations according to both methodologies gave us the following results. The migration potential according to the current (MP = 0.35) and proposed (P = 0.27) methodologies both accord with reality. The two methodologies give approximately identical results, as number close to 1 are not much changed by use of the cube root.

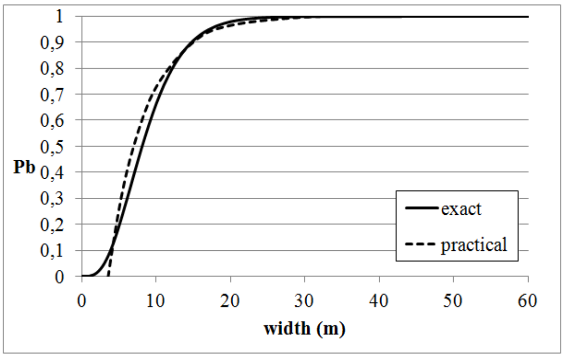

Fig. 5 Category roe deer – dependence of Pb on width of the overpass (m)

V. Conclusion

The existing methodology for determining migration potential according to the approved technical conditions of the Ministry of Transport of Czech Republic and the newly proposed methodology for quantifying migration potential of freeway overpasses and underpasses has been described. The methodologies have been compared and the newly proposed one has been found to be in the close concordance with reality. It is suited especially to medium-sized and large mammals, is mathematically correct, and its applicability was tested by monitoring existing green bridges and underpasses. The newly proposed methodology provides a reliable tool for designers and environmentalists.

TABLE V
P_B: The Constants α, β, γ and δ for the Individual Categories of Fauna

Category	α	β	γ	δ
Red deer	3.8	1.9	0.12	2.3
Roe deer	4.1	2.2	0.22	3.6
Red fox	4.8	3.2	0.22	4.2

Acknowledgment

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