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DATA ENVELOPMENT ANALYSIS FOR TECHNOLOGICAL, ENVIRONMENTAL AND ECONOMIC ANALYSIS OF MOTORWAY UNDERPASSES

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Abstract

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Underpasses play an important role in ensuring permeability of line traffic structures (motorways, expressways) for feral species. There are many studies, articles and methodological guidebooks available describing proper design principles for technical parameters of underpasses and their placement within the terrain. Width, height and length are the main technical parameters affecting wildlife migration. Wildlife behaviour and their requirements for the mentioned technical parameters of underpasses also have been examined in depth. In practically all cases, underpass functionality grows with increasing width and height. Of course, this also results in greater construction costs. The objective should therefore be to find a balanced compromise enabling "sufficient" functionality while maintaining "reasonable" costs. Data envelopment analysis (DEA) provides a way to identify "good" solutions in the sense of "sufficient" underpass functionality with "reasonable" total costs. Underpass functionality calculations were based on a methodology for calculating migration potentials (Žák and Florian, 2013). Total costs were established according to actual construction work prices in the Czech Republic, including prices for preparations, design, construction, maintenance, and demolition. The results indicate that DEA can be used to find "good" solutions and can be of assistance in particular when planning measures to ensure motorways are permeable to wildlife.

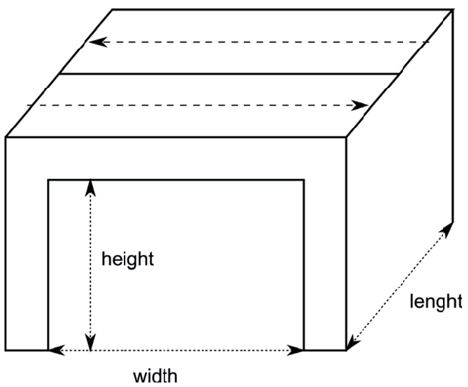
Keywords: motorway bridges, wildlife migration, data envelopment analysis, underpasses, total costs, migration potential

INTRODUCTION

Cases wherein wildlife are insufficiently able to cross motorways can result in population fragmentation (i.e. division of territory into parts so small that they prevent long-term species survival). Special structures (overpasses, green bridges, and underpasses) are therefore built to ensure motorways are permeable. Other possibilities include to use existing bridges over waterways, roads, and uneven terrain. In certain cases, these bridges can be used for migratory purposes even without modifications, while in other cases it is necessary to design increased width or height or to modify their surface or system of construction in order to increase their functionality. The present paper is about analysing underpasses. While overpasses are undoubtedly also effective, for the time being data envelopment analysis (DEA) input parameters do not enable resolving both underpasses and overpasses simultaneously. A method is being developed which will in future enable analysis of all types of migration structures using the DEA methodology, and the first results will be available in the near future.

Optimal migration underpass design must include determination of underpasses' functionality (migration potential) as precisely as possible. Inaccurate migration potential calculations can result in unnecessary cost increases or insufficient utilization for migration. These principles are described more extensively in such studies as Davenport and Davenport (2006), Johnson *et al.* (2013), Huijser *et al.* (2009), Millions and Swanson (2007), Myšková and Žák (2013).

The methodology for calculating migration potential was taken from Žák and Florian (2013). Migration potential (*P*) is calculated as the product of the ecological and technical migration potentials, which are dependent upon technical parameters of the underpass, and specifically height, width and length (see Fig. 1).



1: *Technical parameters of the underpass*

Many high-quality scientific studies have been carried out regarding behaviour of individual species and their requirements for technical migration potential of migration structures (e.g. Davenport and Davenport, 2006; Hilty *et al.*, 2006; Kendall *et al.*, 2008; and Little *et al.*, 2002).

The presence of individual species, including descriptions and maps of migration corridors and evaluation of functions of the surrounding environment, has also been described in detail (e.g. Hilty *et al.*, 2006; Johnson *et al.*, 2013; Kutal and Suchomel, 2014; and Pearce and Boyce, 2006). The National Cooperative Highway Research Program has sponsored several projects concerning migration corridors and measures. Especially noteworthy is Report 615 (Bissonette and Cramer, 2008), which presented research-developed guidelines for the selection, configuration, location, monitoring, evaluation, and maintenance of wildlife crossings. Based on research findings, the team developed an interactive web-based decision guide protocol offering advice in selecting, configuring, and locating various crossing types, as well as suggestions for their monitoring, evaluation, and maintenance. An earlier report (Clevenger, 2007) explores Banff National Park in Alberta, Canada, which has been a testing site for innovative passageways to mitigate the effects of roads on wildlife. The Trans-Canada Highway bisects that park, but a range of engineering mitigation measures, including a variety of wildlife underpasses and overpasses, has helped maintain large mammal populations for the past 25 years and allowed the gathering of valuable data about wildlife crossing structures.

The situation of migration corridors in the Czech Republic has been well mapped by an expert team. Detailed information can be found in Anděl *et al.* (2010) and other research reports from this team.

Many researchers have dedicated a great deal of attention to monitoring migration. Areas specially modified for retaining tracks, such as by adding sand or soil, had previously been used to record migrations. The authors of the present paper have experience using their own camera system, which is based on modified motorway cameras. Recently, photo traps have been used due to their low price and unhindered mobility. Information on various types of monitoring can be found in, for example, Derworitz (2013) and Mata *et al.* (2005).

A number of authors have published studies and various guidebooks including recommendations for proper implementation of measures to ensure permeability of motorways. The apparently most extensive research and related monitoring has been systematically carried out in Canada (see Ament *et al.*, 2008; Clevenger, 2007; Clevenger, 2012; and Clevenger and Huijser, 2011). Other summaries can be found in such sources as Darling (2014) and Millions and Swanson (2007). Recommendations generally concern appropriate surfaces for underpasses as well as their height and width for individual species. Emphasis is given as well to limiting glare and traffic noise. Careful fencing along the entire motorway between migration structures is also very important. Other authors have noted that wildlife need some time to adapt to new conditions, sometimes as much as 3 to 5 years (e.g. Forman *et al.*, 2002). Suitable structure types and descriptions of their design principles can be found in such works as Crooks *et al.* (2008), Crooks and Sanjayan (2006), and Mata *et al.* (2005).

A very relevant study was presented by Ruediger (2006). It deals with relationships with affected institutions as well as with the prices and effectiveness of individual underpass types. That author notes that increasing an underpass's dimensions raises costs, but this does not necessarily bring a corresponding gain in migration potential for he given species. "Biologists," he states, "should recommend the most cost-efficient design that will work for the target species."

Individual recommendations and principles for proper design of migration structures can be summarized in the following points:

1. Underpasses should be as high and wide as corresponds to the requirements of those species present.
2. Underpasses should be as inexpensive as possible.

3. When constructing underpasses, it is important to use proper technology to minimize environmental impacts.
4. Overly generous dimensioning of underpasses makes a motorway unnecessarily expensive.
5. Fences, not migration structures, should be used to prevent wildlife-vehicle collisions.
6. Careful continuous fencing on both sides of the motorway between migration structures is necessary.
7. Migration structures should be designed in locations where wildlife is concentrated and with parameters corresponding to said wildlife's requirements.
8. Migration structures should be monitored over the long term and the experience and knowledge used to design future migration structures.
9. Wildlife most frequently adapts to newly built migration structures within 2–5 years.

The aforementioned principles make it clear that the described layouts have been investigated quite thoroughly, and particularly where migration structures were monitored over the long term. Nevertheless, designs for new structures are based mainly on empirical experience and general principles. No study has been yet published that would in a mathematically precise way optimize the costs of underpasses (their dimensions) and their migration potential. The cost-benefit analyses by Huijser *et al.* (2009) probably came closest to this goal. Cost effectiveness has also been studied by van der Grift *et al.* (2013). As stated above, an underpass's low price and high migration potential are in opposition to one another. It is difficult to design optimization methods to find the best solution. Environmentalists usually give preference to motorways having greater permeability (high migration potential) while investors (understandably) prefer smaller budgets.

This paper therefore applies DEA to finding "good" solutions, which means solutions that ensure relatively sufficient migration potential for reasonable costs. We employ our own experience, a great deal of our own data, and our own methodologies to define structures' migration potential (Žák and Florian, 2013).

MATERIALS AND METHODS

DEA is a statistical method which results in so-called "good" solutions. In our case, it is apparent that an underpass's technical and ecological migration potentials need to be used as inputs for the analysis. Another important input is total costs, which means costs for preparations, design, construction, maintenance, and demolition of the underpass after its period of usability ends. If an existing motorway bridge is to be used for migration, then potential additional costs to increase its functionality are recorded as a percentage of its original price.

Another problem is to obtain a sufficient amount of relevant, error-free data. The authors have at their disposal relevant data from continuous monitoring since 2005. These are records from a camera system located on the section of the D1 motorway from Lipník nad Bečvou to Bělotín (originally designated as D4704). For each underpass, the number of wild animals that appeared near the underpass was recorded. It was then investigated whether the given species attempted to cross and whether this attempt was successful. The number of successful crossings was subsequently evaluated. Data acquired using this method was then supplemented with findings acquired by classic monitoring methods, which means direct observation (including consultations with people knowledgeable about local conditions), tracks, faeces, and vocalizations.

Wildlife occurrence was recorded for three categories:

1. Large mammals – L (deer, bear, wolf, elk).
2. Mid-sized mammals – M (roe-deer).
3. Small mammals – S (fox, marten, polecat, badger).

In subsequent years, the research employed photo traps, characterized by their affordability and especially their mobility. They were used particularly at selected underpasses on the D1, D3, and D11 motorways as well as the R6 and R35 expressways.

There came a quantitative and qualitative change in 2013, when the authors began participating in EUREKA project LF13008 "Integrated Artificial Intelligent System for Detecting the Wildlife Migration". It aims to develop an automated system for recognizing individual wildlife species from video footage. Funding from this project was used to acquire a large number of additional photo traps. The availability of a beta version of the aforementioned recognition system enabled the evaluation of large amounts of data. In the past two years alone, a total of 264 000 records with 45 678 animals were evaluated. This contributed to refining the methodology for establishing the technical migration potential of underpasses and provided further high-quality data for DEA.

Costs are an important DEA input parameter. It must be emphasized that it is necessary to enumerate all costs for preparations, design, construction, maintenance, and demolition of the structure after its service life ends. Motorway bridges are designed with an expected service life of 100 years, with migration structures having the same expected service life. If a structure has a shorter life, it is necessary to include costs for its demolition and reconstruction, or reconstruction of its parts having a life shorter than the expected 100 years. Of course, all planned repairs (replacing expansion joints, bearings, top layers) and maintenance (painting, inspection, etc.) are included. In the Czech Republic, construction work is very frequently overpriced (e.g. Fadrný *et al.*, 2010), and particularly if the investor is financing the construction through public funding. In contrast to certain other EU countries, entire motorway sections in the Czech

Republic are being tendered for amounts in CZK billions. It can therefore be expected that motorway prices will decrease in future after appropriate measures have been taken. The prices of special migration structures are more difficult to determine than are those for usual motorway structures, as they are mostly atypical and a direct comparison with similar existing structures cannot be made. This study included construction work prices net of all unnecessary negative aspects. The present study will therefore be usable without modifications in the Czech Republic in future should the system of procurement and public contract monitoring become similar to those in other, more developed EU countries.

Technical migration potential was calculated according to the methodology described in Žák and Florian (2013). In our case, it is determined mainly by bridge span (underpass width) and underpass height. It is also influenced by traffic disturbances, with positive effects from noise barriers and measures limiting glare from vehicles. When endeavouring to increase a bridge's technical migration potential, the first options offered are to increase its span (widening the underpass) and suitably to modify the surface under the bridge. Bridge width (underpass length) is given by the road type and location, and so potential decreases cannot be expected.

Ecological migration potential was established by an experienced ecologist on the basis of background documents (migration corridor maps, migration studies, monitoring results) and an original survey.

DEA models are designed as specialized model instruments for evaluating the effectiveness, efficiency, and productivity of homogenous production units. DEA involves the use of linear programming methods to construct a non-parametric piecewise surface (or frontier) over the data, so as to be able to calculate efficiencies relative to this surface. DEA models derive from the concept that for each given problem there exists a so-called production possibility set consisting of all possible (feasible) combinations of inputs and outputs. The set of feasible possibilities is determined by the so-called efficiency limit. Production units with combinations of inputs and outputs lying on the efficiency limit are considered as efficient ("good") units.

Our solution uses the BCC model, designed in 1984 by Banker *et al.* (1984). This model assumes variable returns to scale; data are contained by a convex set and therefore more than one unit can be designated as efficient. The model can either maximize outputs (output-oriented) or minimize inputs (input-oriented). DEA was used in Issever Grochová *et al.* (2014), where the effectiveness of extended EU countries from economic and environmental indicators point of view was evaluated.

A mathematical representation of the dual input-oriented BCC model is shown below. Let us assume we have units $U_1, \ldots, U_n$. Also assume we have m inputs and r outputs. We denote the input matrix as $\boldsymbol{X} = \{x_{ij}, i = 1, \ldots, m, j = 1, \ldots, n\}$ and the output matrix as $\boldsymbol{Y} = \{y_{ij}, i = 1, \ldots, r, j = 1, \ldots, n\}$. The model for unit U_q is formulated as follows, minimizing the function

$$z = \theta_q - \varepsilon(1^T s^+ + 1^T s^-)$$

under the conditions

$$X\lambda + s^- = \theta_q x_q,$$

$$Y\lambda - s^+ = y_q,$$

$$1^T\lambda = 1,$$

$$\lambda, s^-, s^+ \geq 0,$$

where θ_q is the efficiency of unit q; x_q is the qth column of the $\boldsymbol{X}$ matrix; y_q is the qth column of the $\boldsymbol{Y}$ matrix; $\lambda = (\lambda_1, \ldots, \lambda_n)' \geq 0$ is the weight vector; s^+ and s^- are vectors of additional variables in limitations for inputs and outputs, $1^T = (1, \ldots, 1)$; and ε is an infinitesimal constant that usually equals 10^{-8}.

Efficient underpasses were taken to be those which had the highest possible migration potential and with the lowest possible costs. Therefore we select:

- minimized input matrix X – costs C, additional costs AC;
- maximized output matrix Y – technical migration potential P_t and ecological migration potential P_e.

For each underpass, migration potentials are inputs for three animal categories: large L, mid-sized M and small S. Results are evaluated separately for each category.

The results matrix provides a large amount of information, in particular identification of "good" solutions (units). Inputs that result in the highest inefficiency and which therefore should be improved where possible are also marked.

RESULTS

As a demonstration of the possibilities given by DEA, this paper presents analyses of 23 selected underpasses for which migration potentials (from previous studies) and dimensions (measured or designed) are known. The underpasses are located on the D1 motorway and the R6 expressway.

Tab. I states the input variables for DEA. Total costs and additional costs are the variables (inputs) to be minimized, while technical and ecological migration potentials are the variables (outputs) to be maximized. Underpass dimensions (width, length and height) are the defining values for calculating technical migration potential.

The DEA model provides a large quantity of results. Tabs. II to IV present selected most usable results for individual wildlife categories (L, M, and S). The first column gives the underpass's

I: *Input data for DEA*

No.	width	length	height	P_e L	P_e M	P_e S	P_t L	P_t M	P_t S	Costs (CZK million)	Additional costs (%)
1	41.00	40.90	7.70	0.89	1.00	1.00	0.76	0.78	0.80	50.31	20.00
2	9.00	36.50	4.20	0.57	0.89	1.00	0.13	0.45	0.80	9.86	0.00
3	13.43	25.50	3.25	0.63	0.89	1.00	0.27	0.57	0.90	10.27	0.00
4	17.25	25.50	5.44	0.20	0.50	0.80	0.69	0.81	0.90	13.20	20.00
5	13.00	25.50	7.14	0.07	0.10	0.28	0.63	0.74	0.80	9.95	0.00
6	14.00	25.50	9.51	0.89	1.00	1.00	0.71	0.77	0.80	10.71	0.00
7	52.00	25.50	8.33	0.20	0.35	0.50	0.77	0.79	0.80	39.78	0.00
8	70.80	27.40	7.11	0.60	0.80	1.00	0.84	0.87	0.90	58.20	0.00
9	25.80	25.90	4.98	0.60	0.80	1.00	0.71	0.79	0.90	20.05	30.00
10	33.80	25.90	8.62	0.62	0.83	1.00	0.88	0.89	0.90	26.26	20.00
11	33.80	25.90	8.03	0.59	0.75	1.00	0.87	0.88	0.90	26.26	20.00
12	28.80	25.90	5.07	0.17	0.35	0.55	0.65	0.71	0.80	22.38	10.00
13	49.80	27.50	4.76	0.42	0.63	1.00	0.63	0.69	0.80	41.09	40.00
14	32.80	37.20	5.20	0.42	0.63	0.89	0.73	0.81	0.90	36.60	10.00
15	114.60	25.50	12.87	0.89	1.00	1.00	0.80	0.80	0.80	87.67	0.00
16	22.00	25.50	6.07	0.63	0.77	0.89	0.78	0.84	0.90	16.83	10.00
17	124.50	25.50	11.25	0.63	0.77	1.00	0.80	0.80	0.80	95.24	0.00
18	106.50	25.50	12.27	0.89	1.00	1.00	0.90	0.90	0.90	81.47	0.00
19	4.80	25.50	2.25	0.65	0.80	1.00	0.01	0.10	0.90	3.67	0.00
20	8.00	25.50	5.00	0.65	0.80	1.00	0.26	0.58	0.90	6.12	10.00
21	4.80	25.50	3.36	0.57	0.77	0.89	0.03	0.20	0.90	3.67	0.00
22	69.47	25.50	8.45	0.42	0.62	0.95	0.78	0.79	0.80	53.14	0.00
23	6.00	25.50	2.00	0.57	0.77	1.00	0.01	0.12	0.90	4.59	10.00

II: *Results for S category*

No. S	dP_e	dP_t	dCosts	dAddCosts	Efficiency
1	0.000	0.099	–46.635	–20.000	0.073
2	0.000	0.099	–6.183	0.000	0.373
3	0.000	0.000	0.000	0.000	1.000
4	0.000	0.000	0.000	0.000	1.000
5	0.714	0.099	–6.273	0.000	0.369
6	0.000	0.099	–7.038	0.000	0.343
7	0.500	0.099	–36.108	0.000	0.092
8	0.000	0.000	0.000	0.000	1.000
9	0.000	0.000	–13.433	–20.103	0.330
10	0.000	0.000	–14.541	–11.074	0.446
11	0.000	0.000	0.000	0.000	1.000
12	0.452	0.099	–18.706	–10.000	0.164
13	0.000	0.099	–37.413	–40.000	0.089
14	0.027	0.000	–9.290	–2.538	0.746
15	0.000	0.099	–83.997	0.000	0.042
16	0.000	0.000	0.000	0.000	1.000
17	0.000	0.099	–91.570	0.000	0.039
18	0.000	0.000	0.000	0.000	1.000
19	0.000	0.000	0.000	0.000	1.000
20	0.000	0.000	0.000	0.000	1.000
21	0.000	0.000	0.000	0.000	1.000
22	0.050	0.099	–49.470	0.000	0.069
23	0.000	0.001	–0.918	–10.000	0.800

III: *Results for M category*

No. M	dP_e	dP_t	dCosts	dAddCosts	Efficiency
1	0.000	0.000	–32.335	–20.000	0.357
2	0.000	0.040	–2.719	0.000	0.724
3	0.000	0.000	–2.012	0.000	0.804
4	0.000	0.000	0.000	0.000	1.000
5	0.000	0.000	0.000	0.000	1.000
6	0.000	0.000	0.000	0.000	1.000
7	0.616	0.000	–20.104	0.000	0.495
8	0.000	0.000	0.000	0.000	1.000
9	0.000	0.000	–7.453	–21.825	0.628
10	0.000	0.000	0.000	0.000	1.000
11	0.075	0.000	–1.072	–1.137	0.959
12	0.000	0.000	–13.097	–8.022	0.415
13	0.000	0.000	–32.221	–36.530	0.216
14	0.255	0.000	–20.310	–5.548	0.445
15	0.000	0.000	–60.146	0.000	0.314
16	0.000	0.000	0.000	0.000	1.000
17	0.167	0.000	–70.688	0.000	0.258
18	0.000	0.000	0.000	0.000	1.000
19	0.000	0.000	0.000	0.000	1.000
20	0.000	0.000	0.000	0.000	1.000
21	0.000	0.000	0.000	0.000	1.000
22	0.340	0.000	–33.037	0.000	0.378
23	0.001	0.071	–0.918	–10.000	0.800

IV: *Results for L category*

No. L	dP_e	dP_t	dCosts	dAddCosts	Efficiency
1	0.000	0.000	–20.306	–20.000	0.596
2	0.050	0.000	–5.113	0.000	0.481
3	0.052	0.000	–4.062	0.000	0.605
4	0.685	0.000	–2.687	–20.000	0.796
5	0.784	0.000	–0.096	0.000	0.990
6	0.000	0.000	0.000	0.000	1.000
7	0.555	0.000	–6.622	0.000	0.834
8	0.000	0.000	0.000	0.000	1.000
9	0.294	0.000	–9.326	–29.983	0.535
10	0.000	0.000	0.000	0.000	1.000
11	0.030	0.000	–1.018	–1.079	0.961
12	0.689	0.000	–12.350	–10.000	0.448
13	0.429	0.000	–31.265	–40.000	0.239
14	0.415	0.000	–24.617	–7.913	0.327
15	0.000	0.000	–44.203	0.000	0.496
16	0.000	0.000	0.000	0.000	1.000
17	0.075	0.000	–54.415	0.000	0.429
18	0.000	0.000	0.000	0.000	1.000
19	0.000	0.043	0.000	0.000	1.000
20	0.025	0.000	–0.101	–10.000	0.983
21	0.000	0.000	0.000	0.000	1.000
22	0.327	0.000	–19.345	0.000	0.636
23	0.071	0.039	–0.918	–10.000	0.800

reference number. The last column states total underpass efficiency. Efficient ("good") underpasses are denoted 1. The closer a value is to 0, the less efficient is the underpass. The values in the second to fifth columns state how much input variables would need to change in order for the underpass to become efficient. Specifically, the columns show how much ecological (column dP_e) and technical (column dP_t) migration potentials would need to increase as well as how much total (dCosts column) and additional (dAddCosts column) costs would need to decrease.

Within the S category, DEA identified nine "good" underpasses (see Tab. II). They include underpasses 19 and 21 which are very low in cost and narrow as well as underpasses 3 and 4 which are relatively more costly but easy to cross.

Within the M category, DEA identified ten "good" underpasses (see Tab. III). Underpass 10 was apparently included due to its low total cost.

Within the L category, DEA identified seven "good" underpasses (see Tab. IV). There are fewer than there are for the M category due to large mammals' higher migration potential requirements. Moreover, it also applies that underpasses fulfilling the larger category's requirements fulfil the smaller categories' requirements as well.

CONCLUSION

The first experiences with using DEA to find "good" solutions for migration structures to ensure permeability of motorways appear to be positive. As expected, the method excludes overly expensive solutions as well as underpasses with unacceptably low technical migration potential for a given wildlife category.

Results so far indicate that neither the least expensive solutions nor underpasses with immense technical potential are necessarily "good" in the sense of DEA.

Based on previous experience, our own data, and the first DEA results, the following principles can generally be recommended in designing underpasses:

1. Proper design of a migration underpass should guarantee a minimum height and width corresponding to the requirements of those species occurring at the location.
2. Underpasses should have a demonstrably determined size ensuring sufficient migration potential for those species present while accounting for costs. Overly generous underpass dimensions make motorways unnecessarily expensive and do not bring any essential increase in functionality.
3. When constructing underpasses, it is important to use technology that minimizes environmental impacts.
4. To prevent wildlife-vehicle collisions, it is necessary to build continuous fencing on both sides of a road. Fencing type must be adapted to those species occurring at the location and constitute for them an impenetrable barrier. Regular inspection of fencing functionality is necessary.
5. Migration structures should be designed in places where wildlife is concentrated and with parameters suitable for those particular animals.
6. Migration structures should be monitored over the long term and this experience used in designing future migration structures. An essential part of evaluation is to calculate the time it takes wildlife to adapt to the newly built migration structures, which most typically is 2–5 years.

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