Technical expertise on

the effects of road noise on call acoustics and the auditory system of the corncrake

This is a non-committal English translation of the original document
https://www.verkehrswende.at/wp-content/uploads/2021/02/Gutachten_210208.pdf

Dieter Schmidradler

St. Pölten, February 8th 2021
[English translation February 19th 2021]

Document history

Date	Modifications
February 4th 2021	Rapid first edition for timely statement to the Austrian Administrative Court
February 8th 2021	• Detailed correction of spelling, grammar and formatting • Chapter „Task description“: additional reference S 34 • Chapter „Function of scenery and trees“: Correction 20 instead of 2 impulses time delay • Chapter “Effectiveness of noise-reducing road surfaces, in particular noise-reducing stone mastic asphalt”: additional reference to [Garniel], Fig. 40 • References: Reference to [Bam] added
February 25th 2021	Non-committal English translation

Task description

According to the current state of knowledge, noise pollution with an equivalent noise level of 45dB(A) for corncrakes means the complete abandonment of the breeding area [Frühauf].

Following on from the unexplained finding of [Pollheimer] from 2007, this report aims to answer the important further question, why there is a partial or total loss of habitat for the corncrake even if the dB(A) rated isophones at certain locations are well below of 45dB(A).

On the basis of the given factors, a professional assessment should be made as to how such a habitat loss can occur and to what extent there is a risk of total habitat loss in the specific case S 34 [Asfinag].

References to the audio documents used

For analysis of the bird call, the following audio file, published according to CC BY-NC-SA 4.0 conditions was used:

Source	https://www.xeno-canto.org/590425
Recorded by	Frode Falkenberg
Location	Øygarden, Vestland, 60°41'21.5"N 4°44'34.1"E
Recording date and time	2020-05-20, 1:30

The following audio file released for non-commercial use from www.salamisound.de was used to evaluate the properties of road noise:

Source	https://www.salamisound.de/1020070-autobahn-ohne
Publishes by	Sebastian Karpp
Location	Autobahn, ohne Fahrbahnschäden, Aufnahme vom Rastplatz aus, ca. 20 Meter von der Fahrbahn entfernt.
Publication year	2011

Analysis tools used

- The sound processing program Audacity in version 2.4.2 was used for evaluation and visualization.
- The calculation of the wavelength-dependent attenuation values was done with the online calculator http://www.sengpielaudio.com/Rechner-luft.htm
- The traffic-dependent sound levels were calculated using the online calculator https://www.laerminfo.at/laermrechner.html

Basic survey on „Balz- und Revierruf“

The corncrake is a ground-breeding bird. The call-type „Balz- und Revierruf“ discussed here is only a small part of the diverse articulation-repertoire of the corncrake (see also [Schäffer], [Fangrath]).

This report examines the question of the acoustic environmental conditions male corncrakes depend on to successfully attract female corncrakes approaching later from Africa.

The call of the corncrake is given in [Garniel] with a sound level of 110dB SPL at 0.3m distance. However, when asked, the author of the source [Schäffer] cited in this document emphasized that the sound pressure measurement was only an anecdotic matter and was not carried out systematically.

The field research reports consistently of the habit of the male corncrake to look for a well-defined relative position to certain structural features in the landscape during his calls. [Budka] even quantifies a preferred location with 34m from trees. The exact cause of this behavior is still unclear.

Despite its territorial behaviour, the bird has to join together to caller-groups in order to achieve the necessary call ranges to attract distant females.

The call of the corncrake can also be heard acoustically over distances of over 1km [Frommolt], [Schäffer].

[Beason] proves that the recording of the species-dependent frequency ranges of birds has been state of the scientific and technical knowledge since the 1930s at the latest. In particular, it has long been clear that, according to the sources cited there, e.g. the pigeon can perceive infrasound and other bird species such as the chaffinch can perceive ultrasound.

In order to adequately assess the specific sensitivity of the corncrake to noise, it is essential to analyse the calls frequency range.

The known state of the art and science also includes the method of determining the noise immission on the basis of a sensitivity or sound evaluation curve adapted to the animal. This shall apply in particular to endangered species or species with special habitat requirements (e.g. [Garniel] on page 114), both of which undoubtedly apply to the corncrake.

Evaluation in the time and frequency domain

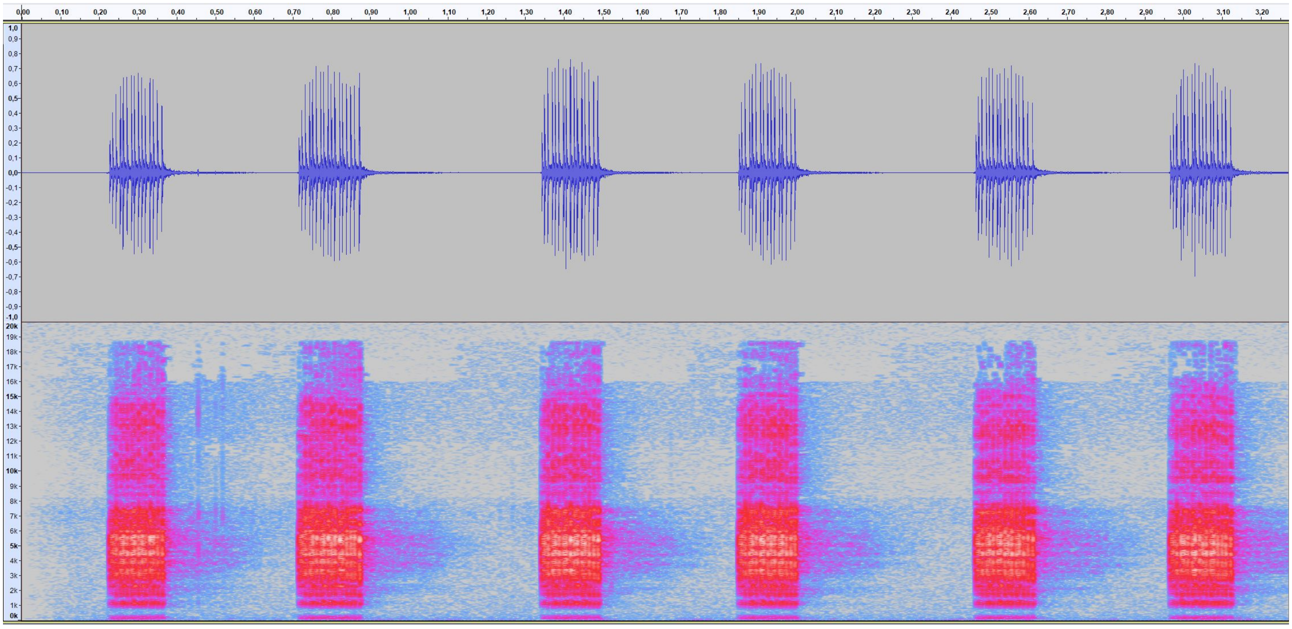

Fig. 1: Wave form and spectrogram: the call of the corncrake extends over a frequency range from below approx. 20Hz to approx. 18.8kHz.

The „Balz- und Revierruf“ call of the male corncrake is described in detail in the literature [Rek]. Each double call consists of (approximately) 2x16 pulses. The bird uses this call both during the day and at night [Schäffer]. The call is often repeated for hours, especially during the night, to attract females.

It is known that corncrakes calling individually have a significantly lower chance of attracting a female, i.e. a single bird with its calling volume is likely to exploit its physical limits.

In the range below 500 Hz, there is something very remarkable in Figure 1: the bird generates a significant low-frequency signal.

Low-frequency components have the advantage, among other things, that animals can particularly communicate over long distances.

The frequency analysis proves a characteristic bass voice in the frequency range significantly from below 40Hz to 500Hz. The carrier of this part of the voice is the pulse sequence in the calls. Thus, the bass voice can be interpreted as the “baseband”.

„Lockruf“ call

[Schäffer] already 1997 documented the bird's ability to generate particularly low-frequency calls: When giving the so-called „Lockruf“, the corncrake keeps its beak closed, which indicates that the spectral component above 500Hz continues to generate the low tone is used, but it literally "swallows" the higher-frequency signal. According to the literature source mentioned before, the call serves to lure the female onto the raw nests built by the male.

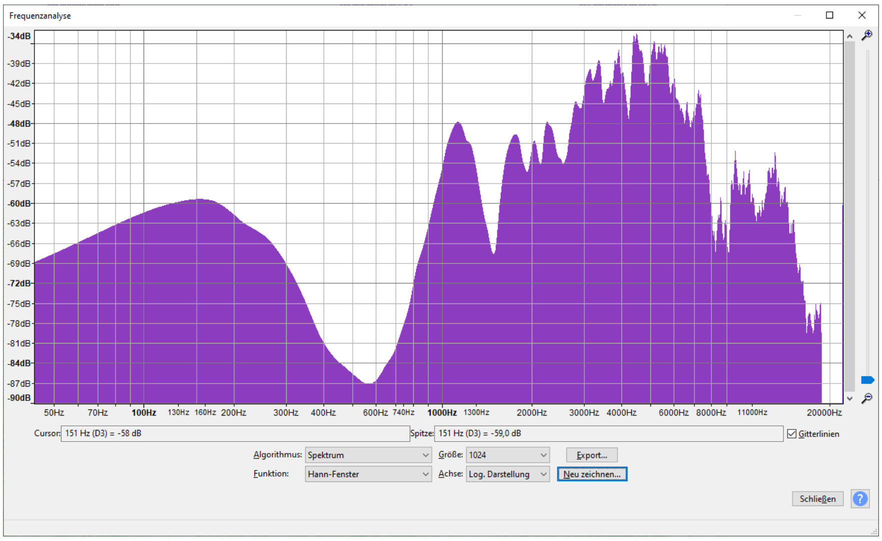

Fig. 2: Solid bass voice of the corncrake with a significant peak-freeuency at around 150Hz.

Function of scenery and trees

The peculiarity of the male corncrake to choose an exact relation to his surroundings while calling has also been proven scientifically [Budka]. An explanation of the purpose of this behaviour has not yet been found.

It is obvious to put the relation of the distance in relation to the time signal of the call.

The preferred distance of an average of d = 34m e.g. from a tree means that a signal reflected e.g. from the tree trunk is perceived by the caller with the following delay:

$\Delta t = 2 \cdot d / c_{luft} = 2 \cdot 34m / 340m/s = 0{,}2s$

On this basis, there is a profound reason to believe that the bird is pursuing the following strategy:

- The bird tries to use the surface structure of the tree or the backdrop to cause a superimposition of the call and the reflected signal in exactly one specific direction. To do this, he must adjust his position after the start of his call sequence so that he himself perceives the best possible superimposition.
- According to the timing diagram, he superimposes his call with the reflected signal, delayed by about 20 pulses.

- Using a different code generated in this way, exactly in the flight between the backdrop and the bird, the call contains a clear additional message that enables the female to fly straight to the caller after taking up the track.

Trees and bushes, if their condition is favorable, have the further advantage [Späh] of specifically amplifying the sound in the direction from which the females are expected.

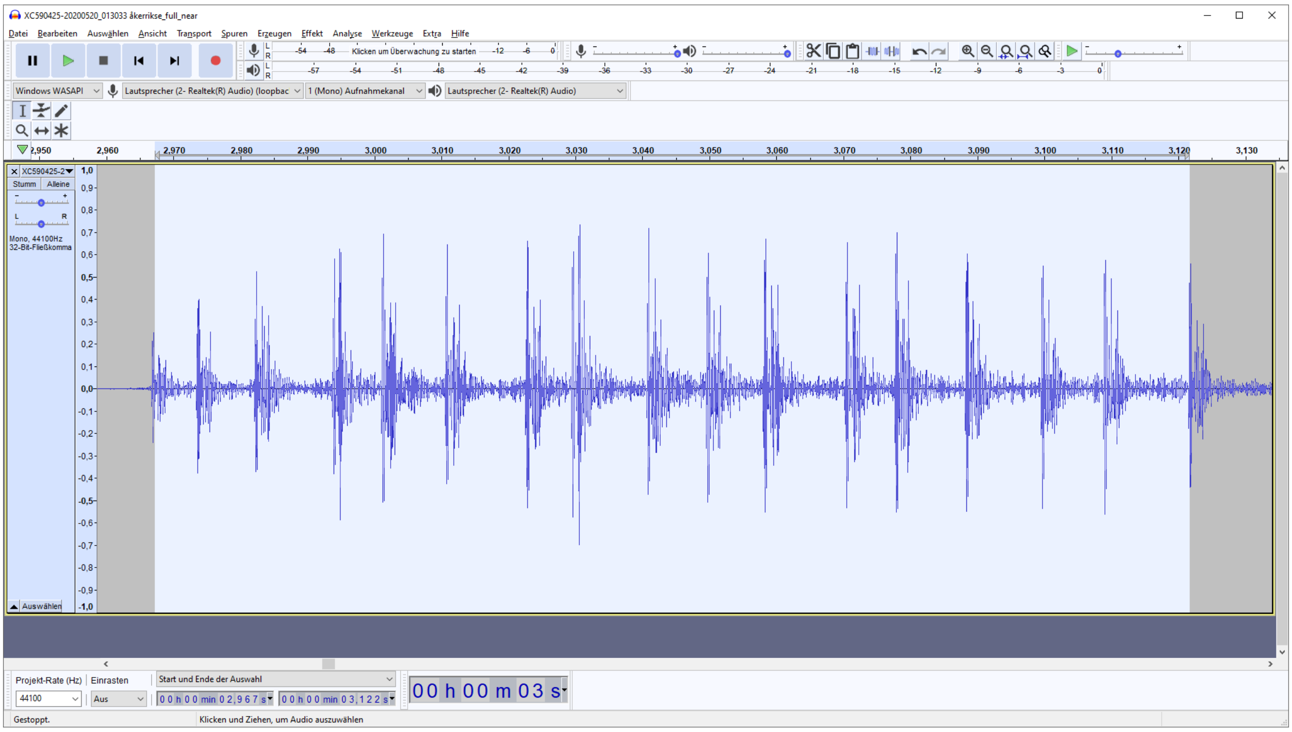

Fig. 3: The mean time between two consecutive pulses is around 10 ms.

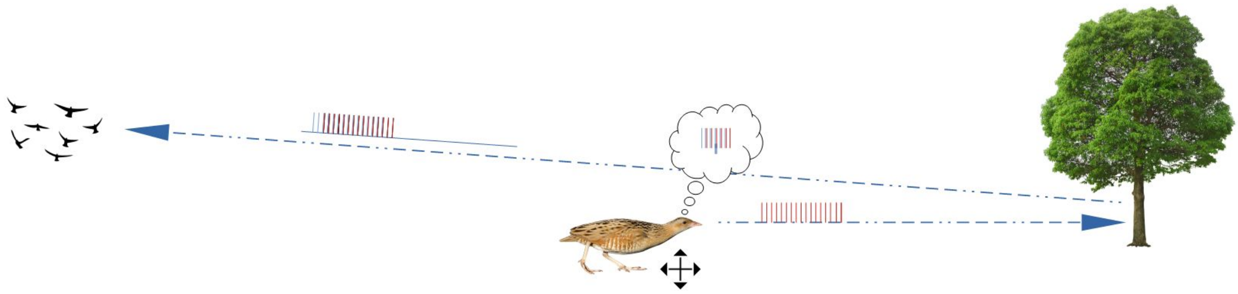

Image 4: The corncrake uses the scenery/tree to attach an exact sender address

Different directional characteristics carrier - baseband

The low frequency range itself and previous explanations on the „Lockruf“ call of the corncrake, it is evident that the sound output of the baseband does not come from the beak, but from the body. This means that the propagation characteristic of the higher-frequency call spectrum is decoupled from the propagation characteristic of the low-frequency tone.

It can be assumed that the bird, due to its anatomy, is able to emit the low-frequency tone in a preferred direction and thereby achieves a significant gain in sound transmission. This could be the key to a particularly long range, especially in the low-frequency range.

Result of the basic survey

- The corncrake's „Balz- und Revierruf“-call covers a frequency range of around 20Hz to 18.8kHz.
- The generation of its significant sound spectrum below 500 Hz is achieved by means of the pulsed signals, in that the approx. 16 pulses emitted within approx. 150 ms are used simultaneously as the carrier for the long-wave frequencies.
- The low-frequency signal component is by no means to be seen as an undesirable side effect, but a fascinating trick by the nature of this bird and a decisive aid to successfully attract females from a long distance.
- The „Lockruf“-call of the corncrake performed with a closed beak corresponds to the low-frequency part of the „Balz- und Revierruf“-call.
- The female corncrake undoubtedly has a corresponding hearing ability in the low-frequency spectral range.
- The bird encodes an additional message in the call in a defined direction in order to enable the female to approach it precisely.
- As will be explained later on sound propagation in air, the corncrake must have a much louder voice than previously assumed.

Basic study on hearing ability of corncrake

Hearing ability below 250 Hz has been proven for 11 bird species [Heffner], according to research carried out now, no corresponding studies are available for the corncrake.

The call of the corncrake, which is made exclusively in the low-frequency range with a peak-frequency of approx. 150 Hz, proves that this low-frequency call is actually directed at the female (luring females to the built nest platforms). Accordingly, there is no doubt that the corncrake (like the 11 bird species already documented) must have an excellent hearing ability in the frequency range below 250 Hz.

For pigeons (Columba live) the perception of infrasound as low as 0.05Hz has been proven [Kreithen], for chickens (Gallus gallus) downto 2Hz [Hill]. At sound frequencies below 50 Hz, both types have a hearing ability that is clearly superior to humans. Even in current scientific publications on the subject at hand it is acknowledged that both the purpose and the functionality of the hearing aid are still largely unexplored [Zeyl et al.].

Jeffrey N. Zeyl et al.

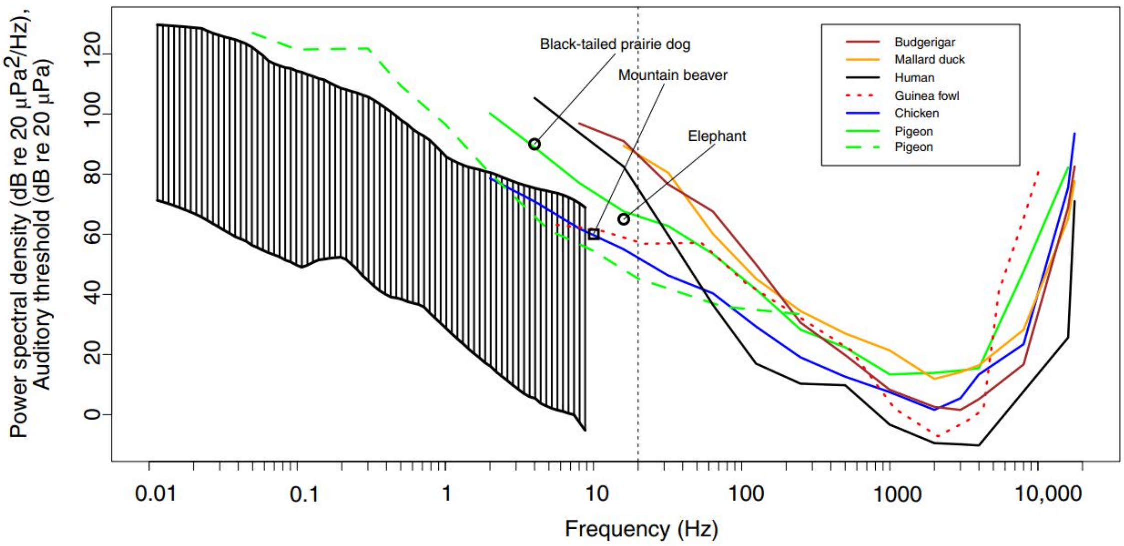

Fig. 5: Picture quotation from [Zeyl]: excellent hearing abilities of the pigeon, chicken and guinea fowl in the infrasound range. According to the corncrake's ability to articulate low frequency sound, the auditory threshold should be similar for the corncrake. The sensitivity curves are designated so that the hearing thresholds are above the expected noise pollution (area marked in black).

Result of the basic study on hearing ability

- For other bird species, there is still no evidence of a corresponding ability to articulate calls in this low frequency range, even for those with pronounced hearing that have been researched so far.
- According to the present survey, the corncrake might probably be the only bird that has the proven ability to generate a significant noise level with its call in this low frequency range.
- Since the corncrake's articulation repertoire also includes the exclusive generation of the low-frequency call as a „Lockruf“, there is no doubt that the corncrake has an excellent hearing ability that is perfectly matched to the low-frequency call.
- With a characteristic hearing sensitivity curve for the corncrake based on Figure 5, the author has investigated how communication with the low-frequency signal may work over significantly longer distances than previously assumed. Since there are no research results for the specific bird and as far as there is no evidence of the correctness of the specifically applied hearing curve, the author dispenses with the model considerations made in this regard.
- According to Figure 5, noise in this frequency range is a central problem for birds with pronounced hearing in the low-frequency range.

Basic study on call propagation in the air

A simplified physical model is used for the considerations presented below

- decrease in the level of a point sound source: -6dB / doubled distance
- frequency-dependent air-damping for 10 ° C and 70% humidity

Frequency-dependent attenuation in air

For an ambient temperature of 10 ° C and 70% humidity, the air-damping values were determined for selected frequencies:

f[Hz]	10	63	125	250	500	1000	2000	4000	8000	16000	20000
Damping [dB/km]	0	0,1	0,4	1	1,9	3,7	9,7	32,8	117	370	510

Air-damping temperature 10 ° C and humidity 70%

Different filters result for different distances, which were approximated in the model creation by linear interpolation between the reference points listed above.

f[Hz]→ Distance[km] ↓	10	63	125	250	500	1000	2000	4000	8000	16000	20000
0,001	0	0	0	0	0	0	0	0	0	0	0
1	0	0,1	0,4	1	1,9	3,7	9,7	32,8	117	∞	∞
1,5	0	0,15	0,6	1,5	2,85	5,55	14,55	49,2	175	∞	∞
2	0	0,2	0,8	2	3,8	7,4	19,4	65,6	234	∞	∞
5	0	0,5	2	5	9,5	18,5	48,5	164	585	∞	∞
10	0	1	4	10	19	37	97	328	∞	∞	∞
20	0	2	8	20	38	74	194	∞	∞	∞	∞

Filter table with frequency-dependent absorption [dB] for different distances

The distance-dependent total attenuation is made up of the wavelength-dependent air attenuation and a purely distance-dependent attenuation.

According to the model, the following decrease in sound pressure level and peak frequency occurs:

Distance [km]	0,001	1	1,5	2	5	10	20
Air-damping [dB]	0	27	32	35	44	49	53
Distance dependent attenuation [dB]	0	60	63,5	66	74	80	86
Total attenuation [dB]	**0**	**87**	**95,5**	**101**	**118**	**129**	**139**
f_{Peak} [Hz]	**4500**	**1130**	**1130**	**1120**	**137**	**120**	**100**

Peak sound pressure level of the corncrake call

The call volume of the corncrake mentioned to this day is 110dB SPL at 0.3m distance refers to [Schäffer].

Since the author of this document encountered severe inconsistencies in the creation of the model, direct consultation with the author was held. According to his own statements, he carried out the sound pressure measurement only as an anecdotic matter.

The waveform of the call shows that the brief peak sound levels that are relevant for the transmission of information are not adequately represented at all in the signal level of a standard sound level meter that integrates over a defined period of time.

From the literature e.g. [Frommolt] it is known that the calls of the corncrake can still be clearly heard by humans at ground level over a distance of one kilometer. The distance between the observer and the bird is subject to disproportionate damping due to the nature of the soil in the habitat, so that plausibly, without ambient noise, from an observation position with a direct line of sight (from the air) it can be plausibly assumed that the call will be perceptible at 1500m.

Under the given assumptions **the peak sound pressure level of the corncrake results in the range of about 125dB SPL at a distance of 1m**. From a technical and scientific point of view, this conclusion also appears plausible in the light of the recently determined peak sound pressure level for the white bellbird [Podos].

Call perception by the female

The following spectrograms show the spectral composition of the signal at a certain distance between the female and a male calling from the center: When approaching from a great distance, only the low-frequency signal component is initially available, only at very short distances is there a significant sound component in higher frequencies contain.

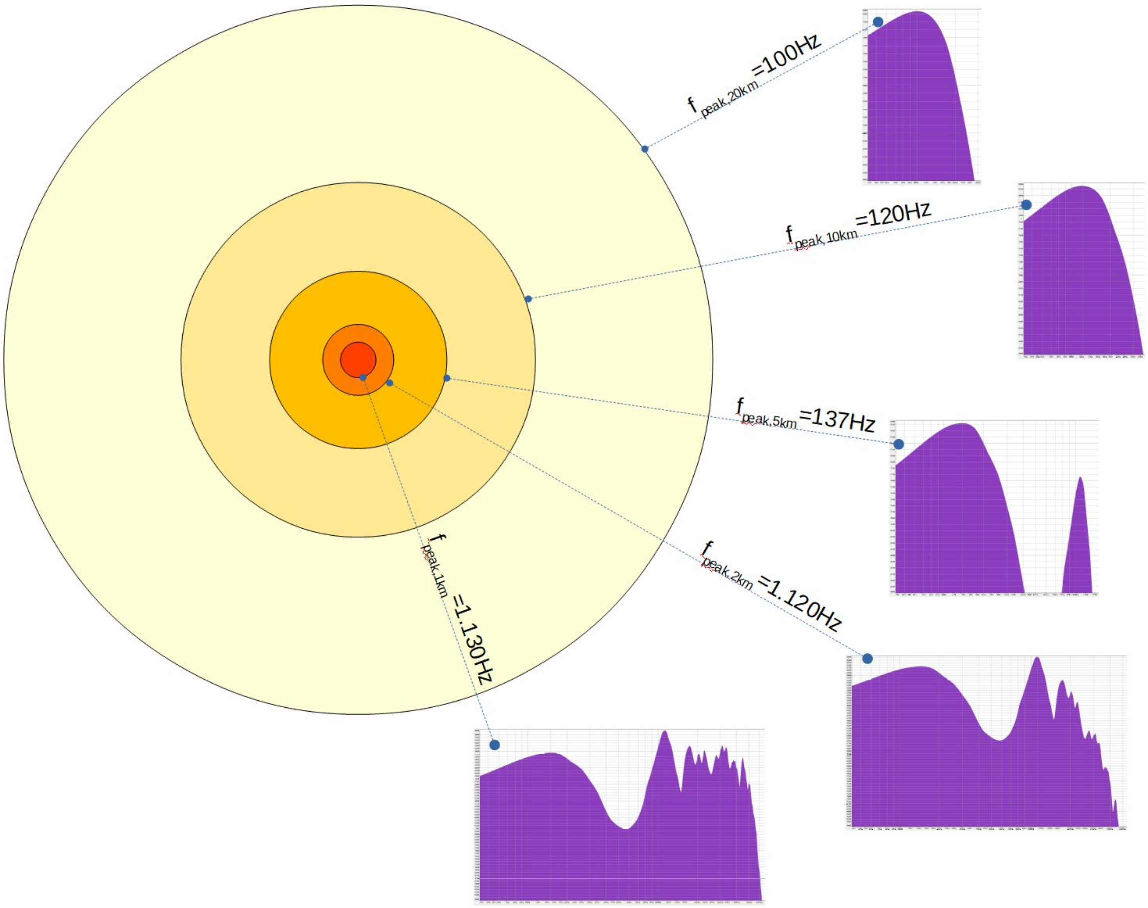

Fig. 6: When approaching, initially only low-frequency sound is contained in the call.

The call of the corncrake can be compared to a flashing light in the fog due to its ongoing change in state: it is still perceived when the noise is only slightly above the bird's perception limit.

However, as soon as a permanent source of interference swallows the call after a short distance, the female can never find the male.

Basic survey on the effect of street noise on the corn crake

[Schimkat] already expressed the suspicion in 2003 that traffic noise could be the reason why the corncrake is no longer able to make his calls.

With the evidence provided that it should be possible to attract females over larger distances than previously assumed by means of low-frequency sound transmission, the assumption is confirmed that the disappearance of the corncrake could be closely related to the dramatic increase in road traffic.

[Dooling] gives the impression like birds can cope with street noise much more easily than humans. The considerations made have been scientifically refuted in the essential points and are no longer tenable.

In particular, neither a dB(A) weighted nor a "Median Bird Hearing Threshold" (p21, Fig. 4) introduced by [Dooling] can give any answer to the question of what effects road noise has on a certain bird species, particularelly to the corncrake.

In the previous investigations of the physical properties of the corncrake call, it was already established that the low-frequency range is an essential part of its ability to communicate.

It must therefore be examined how the actual spectrum of the road noise can affect the bird's communication capabilities.

In [Rek] only the integrity of characteristic features in relation to the territory behavior on site was examined.

It has now been proven that higher-frequency signal components are lost with increasing distance. In order to perceive the calling male from a greater distance, the female is primarily dependent on sufficiently low ambient noise in the low frequency range.

The dB(A) rating, which is tailored to the human ear, falsifies precisely this spectral range and may lead to the loss of habitat in the vicinity of roads identified by [Pollauf] even if the effective noise exposure is well below 45 dB(A).

It is therefore necessary to check whether the low-frequency sound component of the useful signal is well below the background noise from the road.

In order to correctly understand the masking of certain frequency ranges at different points of the endangered habitat, the following methodology was chosen:

- Use of an audio recording of traffic noise right next to the road
- Use of the same filter curves for air damping as for the corncrake call
- Simplified line sound source model for determining the attenuation
- No consideration of ground damping, since the female flying towards the calling bird is relevant and not the caller

- Position the calling male at the most favorable measuring point (furthest away from the S 34)
- Neglect of the second sound source (B 39 - "Obergrafendorfer Straße")

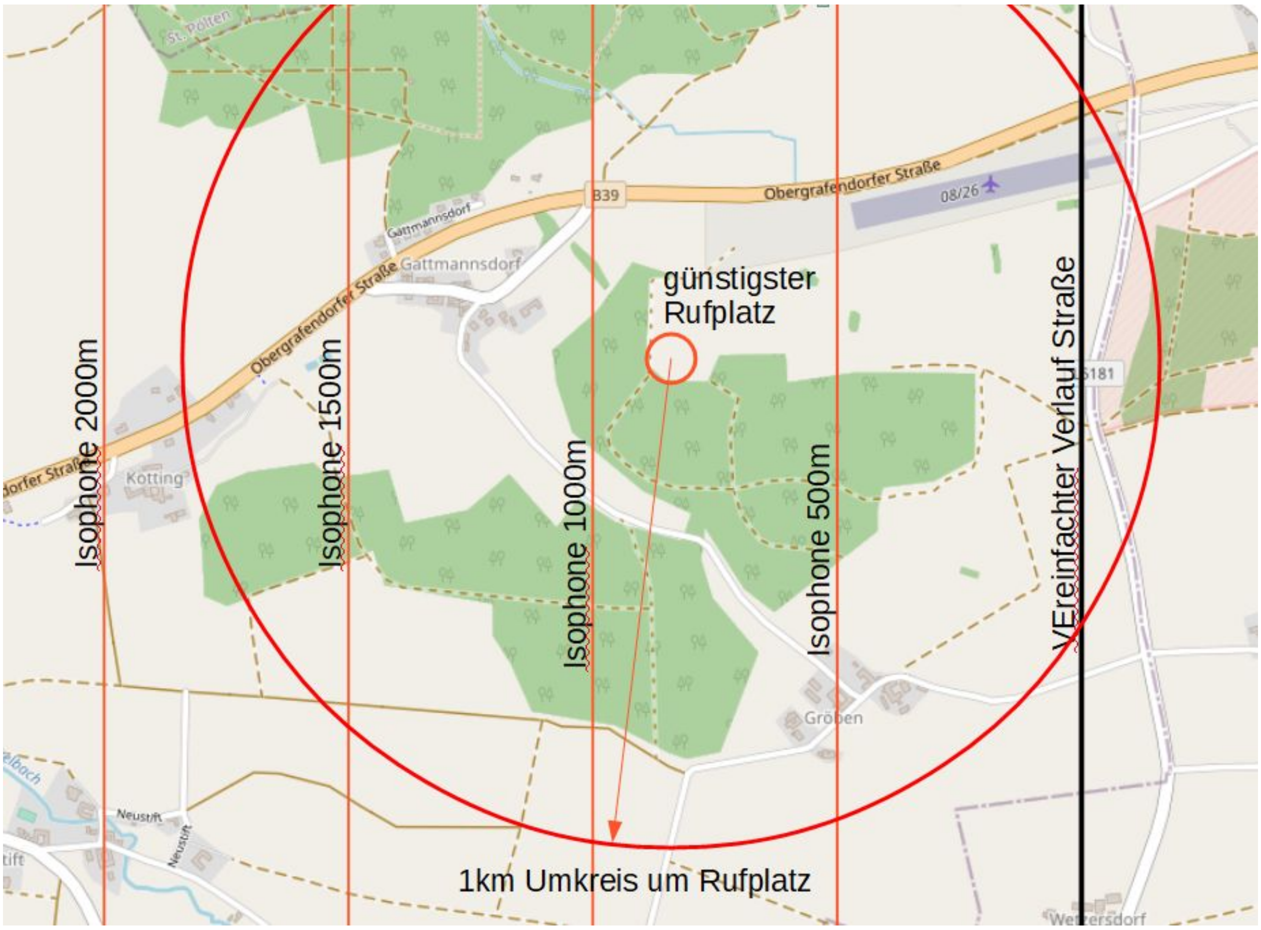

Fig. 7: Simplified model and spatial allocation at the GÜPL (i.e. former „Garnisonsübungsplatz“)

The specified traffic noise calculator was used to determine traffic noise diagrams for the breeding area based on the nightly traffic figures used by the project applicant, which correspond to the isophones shown in Figure 7.

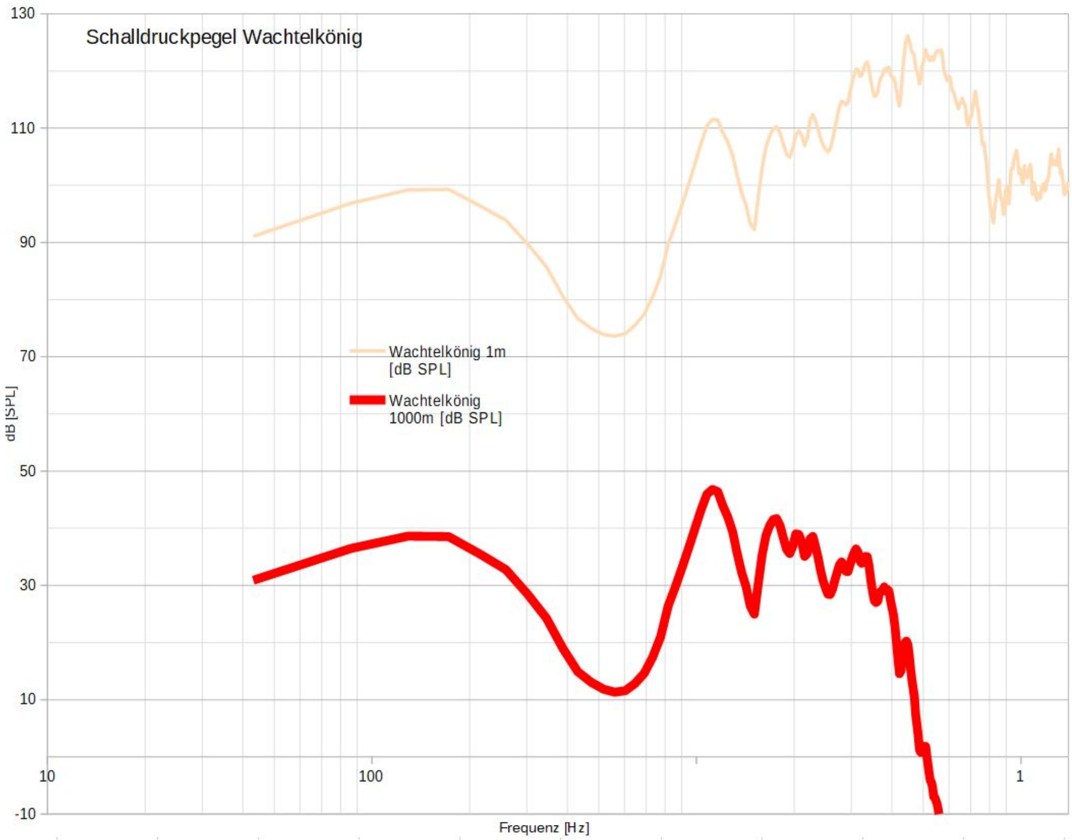

Fig. 8: Direct comparison of the corncrake call next to the bird and at a distance of 1km

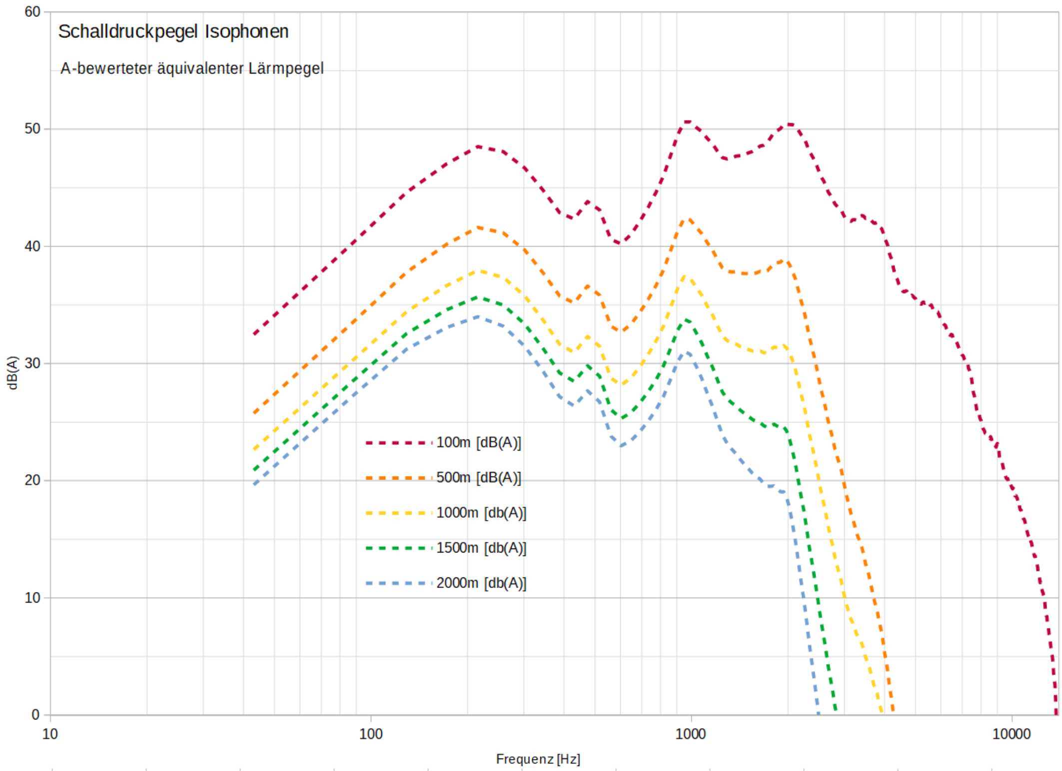

Fig. 9: A-weighted sound pressure level

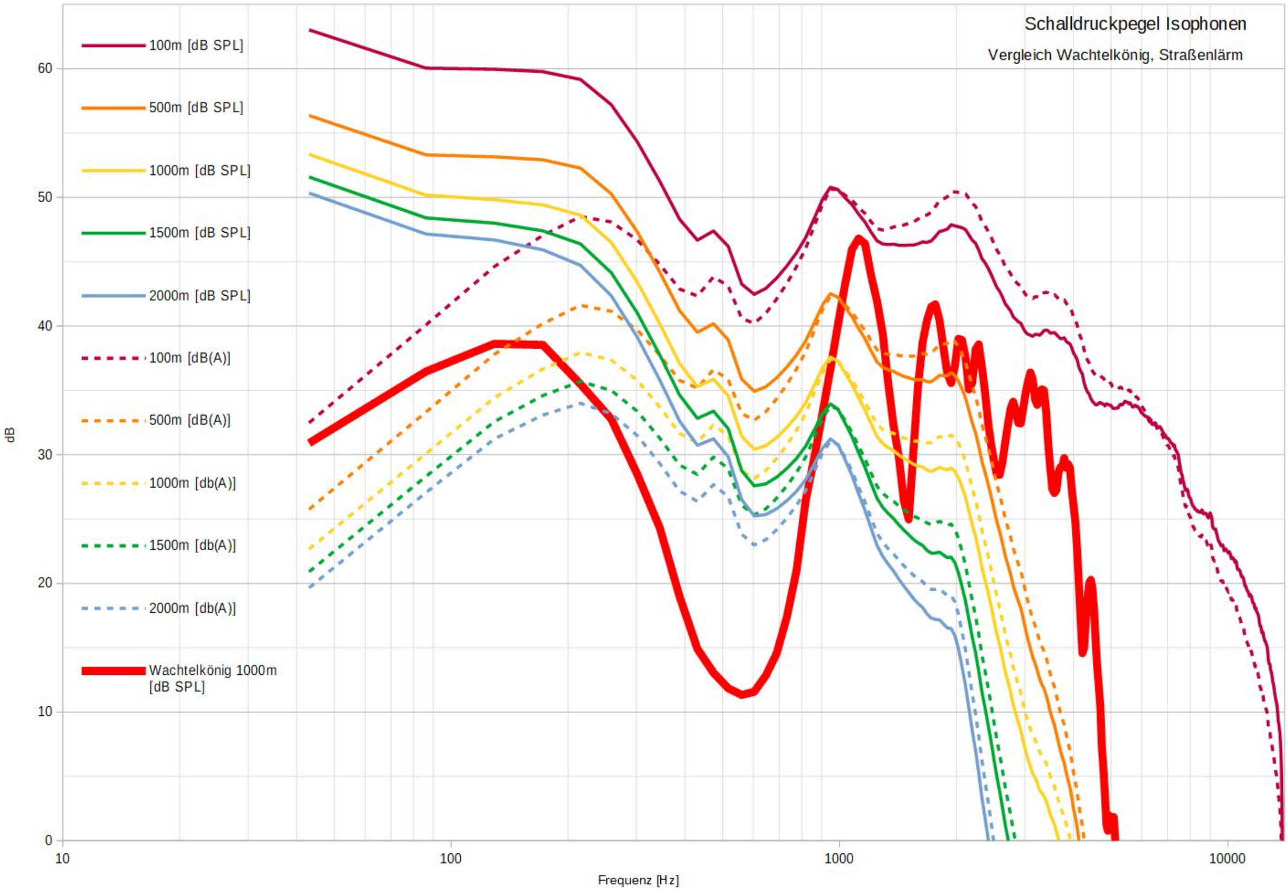

Fig. 10: Comparison of the effective sound pressure level with and without A-weighting and the call of the corncrake.

The spectral comparison of road noise and bird calls leads to the following conclusion:

- The dB(A) rated isophones falsify the spectral range up to 500Hz relevant for bird calls. No statements about the effectiveness of noise protection measures on the street, rated in this way, can be derived.
- A call to the south, north or east gets lost within short distances:
    - There is constant noise exposure to the south and north along the entire course of the road.
    - Towards the east, the caller has an insurmountable "sound barrier" in front of him. Females who decide to fly east of the road further south at the beginning have not the slightest chance of noticing the corncrakes calling.
    - Towards the west, the low-frequency noise level on the road only decreases slightly over the distance. Even the curve of the isophones 2 km away from the road shows that the bird has no way of using the unique ability to call over long distances using a low-frequency voice when the road noise level is actually time-invariant.

Call activity also during the day, effects on other bird species

Why the project applicant assumes in his simulations that the habitat suitability for the bird can only be ensured during the night is not understandable. It is known that corncrakes are active both during the day and at night and generate corresponding calls during the day, even the "Balz- und Revierruf"-call discussed here [Schäffer].

Fig. 11: Isophones for daytime traffic. For birds, the immission on which the simulation is based is still relevant in the air and not on the ground. The simulation parameters are very conservative here with regard to immission points in the air. In fact, at a higher altitude, it can be assumed that the sound pressure levels are significantly less favorable.

Compliance with the maximum noise levels have to be related to the entire activity period of the birds.

In addition, [Garniel] also names a general 47dB (A) border isophone as an indicator of considerable impairment for all bird species (page 49).

With the traffic volume of 21,200 vehicles per day on which the project applicant is based, the limit isophone is calculated to be 1,000 m. In other words, the entire GÜPL is affected by a noise-overflow for birds, and thus a dramatic loss for the entire biodiversity at the GÜPL has to be assumed.

<u>Effectiveness of noise-reducing road surfaces, especially noise-reducing stone mastic asphalt</u>

A look at a manufacturer's brochure [Bam] or [Garniel], page 236, Fig. 40 illustrates the fact that noise-reducing stone mastic asphalt has no or possibly even a disadvantageous effect on the corncrake:

> *Ultimately, this results in a frequency shift towards the lower tones that are perceived as more pleasant and a disproportionate reduction in the noises in the frequency range above 1000 Hertz, which is perceived as rather unpleasant.*
> *[translated citation from German source]*

The effect of noise-reducing road surfaces is therefore at least partially aimed at shifting noises perceived as annoying to the human ear into a wavelength range that is even more adverse for the corncrake.

Statements or counter-questions from leading international experts contacted in the matter fundamentally call into question the chosen approach of making a road (that cannot be approved with a normal road surface) suitable for the corncrake by means of a noise-reducing road surface:

Excerpt from comments from
Dr. Lars Schade, German Federal Environment Agency, Section "Noise Reduction in Traffic" *[translated citation from German source]*

- *It would be crucial to know which aspects of noise in an area determine whether the corncrake considers this area as a habitat. Can this be adequately described by an A-weighted continuous sound level? Are level peaks relevant? Or tonal aspects? Or maybe times of the day or the season to which you could effectively respond with time-limited speed restrictions?* ***Without specific knowledge of these aspects, the question cannot actually be answered reliably.***
- ***It seems unlikely to me that the choice of road surface*** *(here we are talking about a few dB differences, A-weighted with only minor spectral change - with the exception of open-pored surfaces)* ***has a decisive influence on the suitability of the area as a breeding and habitat for the corncrake****. It also seems unlikely to me that stone mastic asphalt would lead to a significant deterioration in the communication between corn kings and the reference surface.*

Analogous statement from a scientist teaching in the subject at an internationally highly regarded technical university:

- *Noise can actually be described with different parameters or characteristics. On the one hand, of course, the "total" sound level is often used as an evaluation criterion, e.g. the mentioned 45 dB (A).*
- *The addition (A) to the unit dB is a frequency weighting that takes certain frequencies less into account in the energetic addition of the individual frequency ranges (tierces). These are frequencies that are generally more difficult to hear or perceive by humans (so-called A-weighting).* ***If, for example, in this case, it is about specific*** *[for the corncrake relevant]* ***frequency ranges of the overall level, one should actually take a closer look at the frequency spectrum.***
- *In the case of noise-reducing road surfaces, the effectiveness actually results from different mechanisms depending on the "asphalt type" / type of mix used.*
- ***In the case of noise-reducing stone mastic asphalt, absorption plays a minor or no role at all.*** *The effect is based more on reducing tire vibrations and reducing aerodynamic noise generation mechanisms between the tire and the road surface. Depending on how strongly which effect is involved, there can also be a shift in the frequency spectrum of the traffic noise.*
- ***How these effects are in detail on the spectrum of the overall noise depends heavily on the boundary conditions*** *(type and composition of asphalt, composition of traffic, etc ...).*

Conclusion

The corncrake generates a low-frequency call that is hardly subject to air damping.
The finding that this call is also given in isolation as a “Lockruf”-call and has a biological function proves beyond doubt that the corncrake is a bird with a distinctive hearing ability in the frequency range below 250 Hz.

This fact, as well as the change in the spectral composition in the direction of lower frequencies calculated for a typical weather condition reveals the gross misjudgment on which the considerations by [Frühauf] and thus also [Kollar] are based, that corncrakes would transmit and receive in frequencies in the range between 4 and 8 kilohertz ([BVWG] page 19, first paragraph). The author himself indicates the strong imponderables associated with an inclusion or non-inclusion, of a dB or dB(A)[1] variable in the roughly simplified habitat model used by [Frühauf] (4.3.10).

Nevertheless, the project advocateswould like to derive a proof from the evaluation scheme, which is largely detached from technical-physical relationships, that the habitat suitability is guaranteed thanks to a noise-reducing road surface and a one-sided project change including excessive deforestation.

The bird's ability to communicate in a much lower frequency range than previously assumed implies that immission considerations relating to the human hearing, e.g. according to the A-rating, are actually not transferable to the corncrake, in particular noise protection measures are largely ineffective if not even counterproductive.

The problem summarized by [Frühauf] in 4.3.13 was confirmed by the investigation of the acoustic characteristics of the bird call:

- The corncrake looks for call points at the greatest possible distance from streets precisely because they achieve a far greater call range in an environment without low-frequency street noise than in a noisy environment.
- With increasing traffic, low-noise time windows disappear between vehicle passages in which birds can successfully make calls over the necessary distances. On a road that continuously generates noise, the bird therefore has no realistic chance of reaching the distant female with its call. This corresponds to the observation that significant habitat losses also occur in zones that are supposedly less exposed to noise [Frühauf] in 4.3.11 and 4.3.12.

With these findings, the widespread loss of habitat of the corncrake across Europe can no longer be explained solely with the loss of suitable natural areas. Various observations also suggest that the corncrake can survive in carefully used agricultural surroundings [Hüttig, Uhl].

In the light of the determined acoustic properties of the bird call and the associated communication options, **the noise pollution emanating from the road traffic network, especially in the low**

1 There is no definition of dB in the entire [Frühauf] report, in particular an allegedly very good correspondence between 47 dB (A) and “the Austrian value of 45 dB” is expressly pointed out (cf. [Frühauf] 4.3.13).

frequency range over long distances, is a more serious problem for the corncrake and presumably for a large number of other living beings - including humans [WDDB] **than yet accepted or admitted.**

Based on a conservatively assumed simulation of the daytime noise situation for flying or tree-dwelling birds, it was determined that the 47dB (A) border isophone, which is critical for all birds, runs about 1000m on both sides of the road. It is therefore not only the corncrake that is severely affected, but also virtually all bird species in the entire GÜPL area.

The established interrelationships between street noise, call acoustics and the auditory system of the corncrake show that **the preservation of habitats for the corncrake is entirely incompatible with the construction of the planned road**.

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Technical training and professional career

<u>Technical and scientific education</u>

- 1980-1988: high school “Bundesgymnasium and Bundesrealgymnasium Wieselburg”, natural science branch
- 1989-1995 study of electrical engineering, Vienna University of Technology, major in industrial electronics and control engineering; among others, diploma examination in the subject of communications and computer technology
- 1996-1999 doctoral thesis at the Institute for Applied and Technical Physics o. Prof. Horst Ebel
- 1999 Rigorosum in the examination subjects Technical Physics and Flexible Automation and Electronics

<u>Professional development</u>

- 1994-1999 Student assistant and later university assistant at the Institute for Flexible Automation
    - R&D apparatus for the analysis of internal engine processes, including spectral analysis for temperature measurement in the combustion chamber of diesel engines using an RGB camera
    - Supervision of several diploma theses, especially in the field of sensor systems
    - Compendium for students on the subject of "sensors and sensor systems"
- 2000-2006: Kapsch AG / Kapsch TrafficCom AG:
    - Development of the competence area for roadside sensors for toll systems
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- 2006: Approval for regulated tade „Technisches Büro - Ingenieurbüro“ in the field of Measurement and process-control, physical measurement technology
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