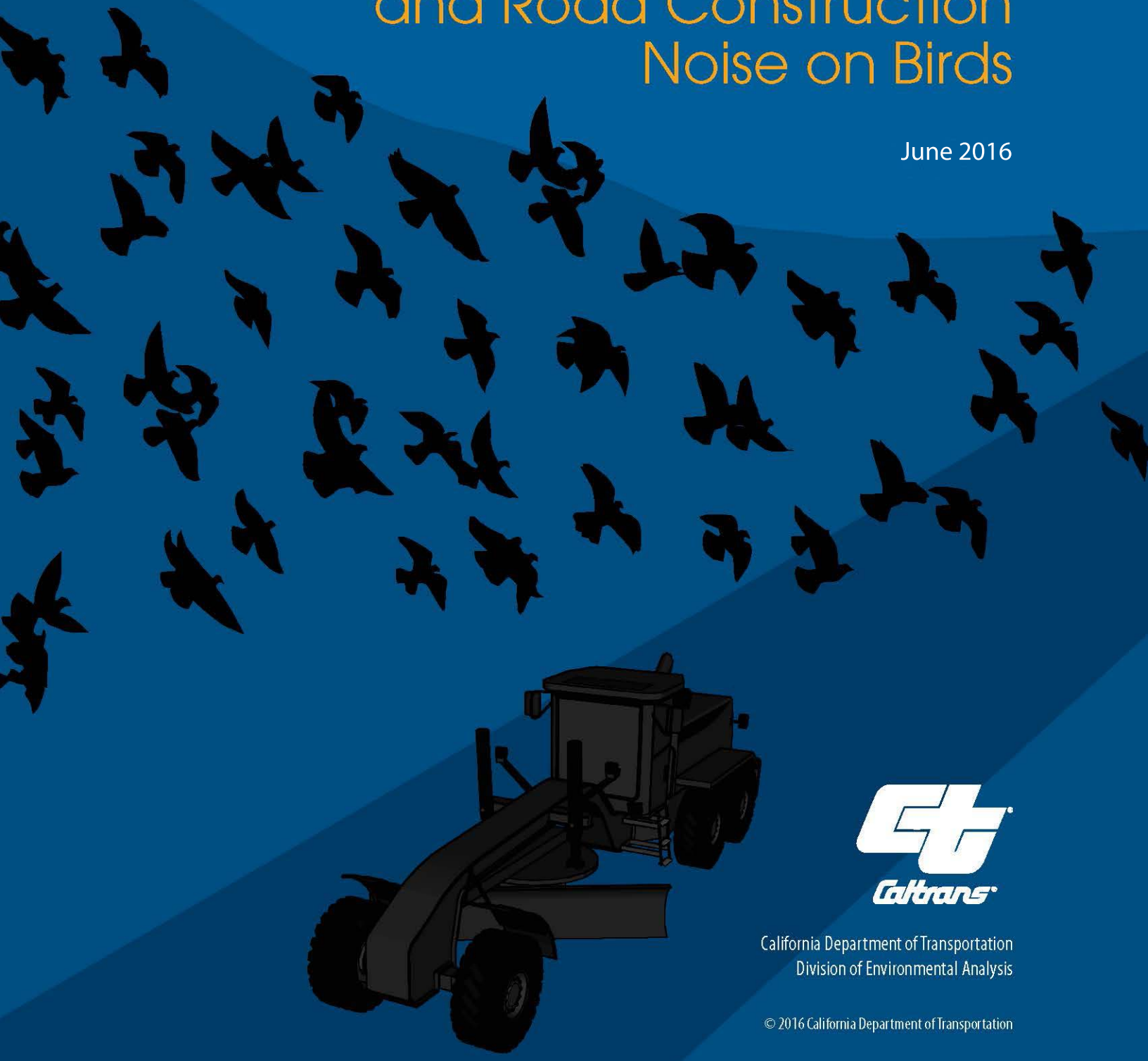
Technical Guidance for
Assessment and Mitigation of the

Effects of Traffic Noise and Road Construction Noise on Birds

June 2016



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15. Abstract

The purpose of this report is to provide Department engineers, biologists, and consultants with guidance related to the effects of traffic noise and road construction noise on birds. This manual covers bird hearing and communication within the highway operational and construction sound environment. The following topics are discussed: stress and physiological effects, acoustic over-exposure, masking, dynamic behavioral and population effects, extrapolation of data from humans and birds to other species. Interim guidelines for estimating the effects of these noise sources on birds is provided.

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Division of Environmental Analysis
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Table of Contents

Executive Summary ... 3
Introduction, Overview, Direction ... 11
A. Definitions ... 11
B. Organization and Purpose of This Guidance Document ... 12
C. Analysis of United States Fish and Wildlife Service (2006) Report ... 12
D. Literature Surveyed in this Guidance Document ... 14
E. Metrics and Terminology ... 14
F. Typical Roadway Operational and Construction Noise Levels ... 15
Table 1. Typical Highway Conditions ... 15
Figure 1. Typical Roadway Noise Levels as a Function of Distance ... 16
G. Relation between A-Weighted Sound Level in and Spectrum Level ... 16
Figure 2: Caltrans Traffic Noise Spectra Showing Differences in Unweighted and Weighted Spectra and Overall Levels ... 17
2. The Bird Ear and Hearing ... 17
Table 2: Construction Equipment Noise Emission Levels (greatest-to-least) ... 18
A. Behavioral Measures of Avian Hearing—the Audiogram ... 19
B. The Hearing Range and Vocalization Spectrum of Birds ... 20
Figure 3: Bird Hearing Thresholds ... 21
C. The Hearing Capabilities of Nestlings ... 21
3. General Principles of the Effects of Noise on Birds ... 22
Figure 4: Potential Effects of Traffic and Construction Noise on Birds ... 23
Table 3: Recommended Interim Guidelines for Potential Effects from Different Noise Sources ... 25
A. Effects of Noise on Hearing in Birds—Threshold Shift ... 25
Figure 5: Threshold Shift in Birds Exposed to Noise ... 27
B. Masking and the Characteristics of Noise ... 28
C. Comparative Masking Effects in Birds—Critical Ratio ... 29
Figure 6: Avian Critical Ratios ... 30
Figure 7: Critical Ratios in Birds and Humans ... 32
D. Understanding the Implications of Masking and Hearing in Noise ... 32
Figure 8: The Effects of Traffic Noise of 84 dBA on Hearing Thresholds of the Typical Bird ... 32
4. Effects of Traffic and Construction Noise on Birds—A Review of Relevant Literature ... 33
A. Overview ... 33
B. Birds and Traffic and Construction Noise ... 34
C. Short-Term Adaptations to Noise Masking ... 39
D. Long-Term Adaptations to Noise Masking ... 41
E. Estimating Maximum Communication Distance between Two Birds Using Laboratory Masking Data ... 41
F. Putting It All Together—Predicting the Effects of Noise on Bird Acoustic Communication ... 42
G. Defining Guidelines for Effects ... 43
Figure 9: The Effects of Anthropogenic Traffic Noise on Four Different Behaviors Based on the Average Bird Critical Ratio Function ... 44
Figure 10: Diagrammatic Representation of Bird Communication ... 45
5. Summary and Overview of the Effects of Traffic Noise on Birds ... 46
6. Estimating Effects of Traffic Noise on Birds, Rationale, and *Interim* Guidelines ... 47
References Cited ... 51
Appendix A: Glossary ... 63
Appendix B: Complete Table of all Behavioral Studies of Hearing in Birds ... 67
Appendix C: Complete Table of all Behavioral Studies of Critical Ratios in Birds ... 69
Appendix D: Fundamentals of Highway Traffic Noise ... 71
Appendix E: Review of Pre-2007 Literature on Effects of Traffic Noise on Birds ... 79
Appendix F: Recommendations for Research to Refine Future Guidance ... 83
Appendix G: A History of the 60 dBA Criterion ... 87

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Executive Summary

Recent literature on the effects of noise in the environment has shown that the world is becoming a noisier place and that the effects of chronic noise exposure on terrestrial animals, including birds, could be significant. Furthermore, with population increases and urbanization, traffic and road construction are major and increasing sources of environmental noise.

A. Overview of this Guidance Document

There is a long-standing concern that roadway construction noise and subsequent traffic noise may be detrimental to wildlife, and especially birds, which relies heavily on acoustic communication. The Endangered Species Act provides additional, compelling, motivation for understanding the effects of traffic and construction noise on federally listed bird species that are in danger of extinction. Effects of construction and/or traffic noise may be nonexistent in certain circumstances, such as when the level of these noises is below natural ambient noise levels, and insignificant in other circumstances, such as when the noise adds very little to existing ambient noise levels.

In contrast, construction or traffic noise that adds significantly to natural ambient noise has the possibility of producing a suite of significant short- and long-term behavioral and physiological changes in birds. These may include changes in foraging location and behavior; interference with acoustic communicate between conspecifics; failure to recognize other important biological signals, such as sounds of predators and/or prey; decreasing hearing sensitivity temporarily or permanently; and/or increasing stress and altering steroid hormone levels. Any of these effects could have long-term consequences and enduring impacts that include interference with breeding by individuals and populations, thereby threatening the survival of individuals or species.

This Guidance Document is an updated version of the 2007 report entitled *The Effects of Highway Noise on Birds* prepared by the authors (Dooling & Popper, 2007).

B. Definitions

Several terms are used in this report. Some of these terms have multiple meanings and are defined herein. Other terms are defined in the glossary.

- **Construction Noise**: Noise produced during the construction of a roadway.
- **Effects**: Any response by birds to traffic and construction noise. This simple definition does not invoke or imply regulatory definitions of “effect” as found in any law or regulation affecting birds.
- **Roadway**: Any paved road on which there is vehicular traffic.
- **Traffic Noise**: Noise produced by vehicles on any paved roadway, ranging from highways to single-lane streets.

C. Findings

A review of relevant literature provided insight on several important issues regarding the effects of traffic and construction noise on birds.

1) Stress and physiological effects:
   a) There are no studies definitively identifying traffic noise as the critical variable affecting bird behavior near roadways and highways.
   b) There are well-documented adverse effects of sustained traffic noise on humans, including stress, physiological and sleep disturbances, and changes in feelings of well-being that may be applicable to birds.
   c) Traffic and construction noise below a bird's masked threshold has no effect.

2) Acoustic overexposure:
   a) Birds are more resistant to both temporary and permanent hearing loss or to hearing damage from acoustic overexposure than are humans and other animals that have been tested.
   b) Birds can regenerate the sensory hair cells of the inner ear, thereby providing a mechanism for recovering from intense acoustic overexposure, a capability not found in mammals.
   c) The studies of acoustic overexposure in birds have considerable relevance for estimating hearing damage effects of traffic noise, non-continuous construction noise, and for impulsive-type construction noise, such as that from pile driving.

3) Masking:
   a) Continuous noise of sufficient intensity in the frequency region of bird hearing can have a detrimental effect on a bird's ability to detect and discriminate between the vocal signals of other birds.
   b) Noise in the spectral region of the vocalizations has a greater masking effect than noises outside this range. Thus, traffic noise will cause less masking than other environmental noises of equal overall level but that contain energy in a higher spectral region (around 2–4 kilohertz [kHz]) (e.g., insects, vocalizations of other birds).
   c) Generally, human auditory thresholds in quiet and in noise are better than that of the typical bird; therefore:
      (1) The typical human can hear a single vehicle, traffic noise, and construction noise at a much greater distance from the roadway than can the typical bird. This fact provides a valuable, common sense, easy-to-apply risk criterion.
      (2) However, the typical human is also able to hear a bird vocalizing in a noisy environment at twice the distance that a typical bird, which suggests, in this case, that relying on human hearing as the primary criterion seriously underestimates the effects of noise on bird communication.
   d) From knowledge of: (i) bird hearing capabilities in quiet and noise, (ii) the Inverse Square Law, (iii) excess attenuation in a particular environment, and (iv) species-specific acoustic characteristics of vocalizations, reasonable predictions can be made about possible maximum communication distances between two birds in continuous noise.

e) The amount of masking of vocalizations can be predicted from the peak in the total power spectrum of the vocalization and the bird's critical ratio (i.e., signal-to-noise ratio) at that frequency of peak energy.
f) Birds, like humans and other animals, employ a range of short-term behavioral strategies, or adaptations, for communicating in noise resulting in a doubling to quadrupling of the efficiency of hearing in noise.

4) Dynamic behavioral and population effects:
   a) Any components of traffic noise that are audible to birds may have effects independent of and beyond the effects listed above. At distances from the roadway where traffic noise levels fall below ambient noise levels in the spectral region for vocal communication (i.e., 2–8 kHz) (Figure ES1), low-level but audible sound in non-communication frequencies (e.g., the rumbling of a truck) can potentially cause may cause physiological or behavioral responses). Because the more recent literature points to noise as possibly having wide-ranging effects on birds, the additive effects of traffic noise and environmental noise must be considered beyond solely the effects due specifically to traffic noise.

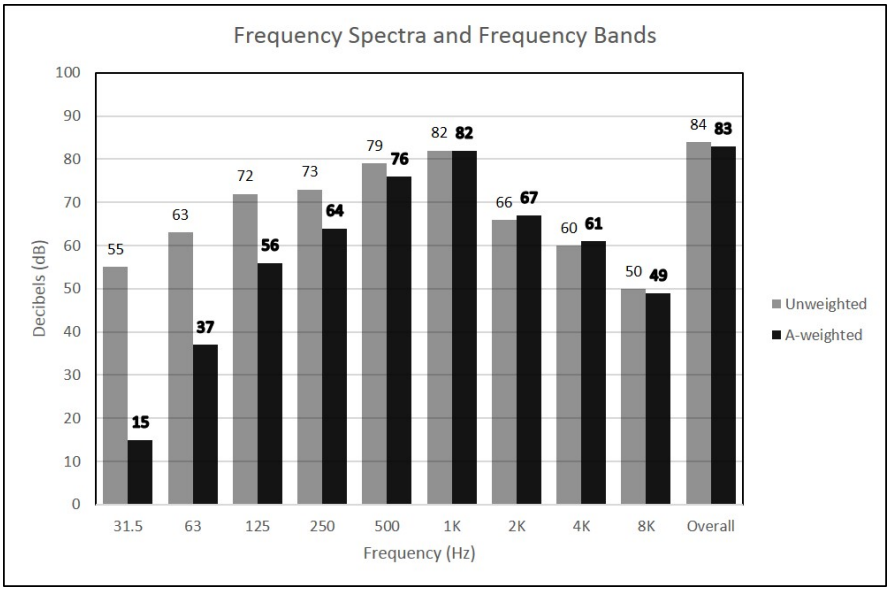

Figure ES1. Caltrans Traffic Noise Spectra Showing Differences in Unweighted and Weighted Spectra and Overall Levels[1]

5) Extrapolation of data from humans and birds to other species:
   a) Since there is substantial variation in bird hearing and behavior, considerable care must be taken when trying to extrapolate data between species, particularly when the species have different hearing capabilities and acoustic behaviors.
   b) Data on human hearing has some relevance to understanding effects of sound on birds. In particular, data on physiological effects in humans may have general implications for birds, but applications to specific situations will require additional study.

6) Much more data are needed on:

[1] Figure from: http://www.dot.ca.gov/hq/env/noise/online_training_module1/slides/slide50.htm

a) Physiological effects of sound on birds.
b) How responses vary between species with regard to masking, hearing loss, and hearing recovery.
c) Hearing in young animals and how it compares to adult hearing.
d) Additional, carefully selected species so there is a large enough database from which to allow extrapolation between species and enable broader generalizations regarding the effects of noise on birds.
e) A broader range of studies, as discussed in detail in Appendix F.

The authors suggest the *interim* compliance guidelines in Figure ES2 and Table ES1 and a science-based approach, using human and avian data from both the laboratory and the field, to address potential impacts of noise on bird species.

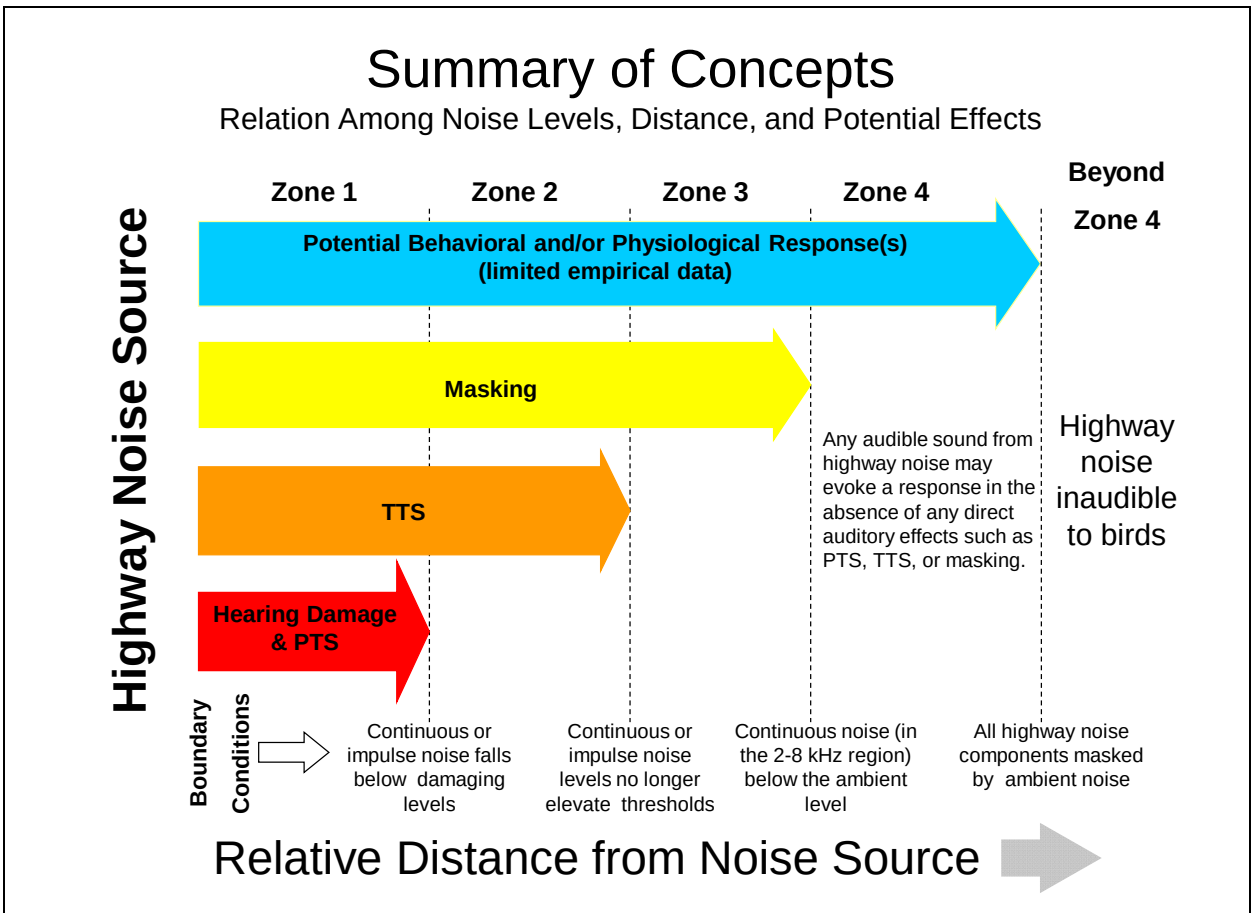

Figure ES2. Effects of Traffic and Construction Noise on Birds

Categories of traffic and construction noise effects on birds with distance from the source. Zone 1 is closest to the source while Zone 4 is farthest away. Sound level decreases farther from the source. See text for discussion.

This Guidance Document reviews four classes of potential effects of traffic noise on birds, as discussed below. The basis for the guidelines for each of the classes differs. Table ES1 provides specific interim criteria.

1. *Behavioral and/or physiological effects*: There are no definitive studies showing that traffic noise exclusively (as opposed to correlated variables) has an adverse effect on birds. While a wealth of human data and experience suggest traffic noise could have a number of adverse effects, there are several studies (e.g., Awbrey *et al.*, 1995) showing that birds (as well as other animals) adapt quite well, and may even appear to sometimes prefer, environments that include high levels of traffic noise. Given the lack of empirical data on this point, it is recommended that subjective human experience with the noise in question be used as an interim guideline to estimate acceptable noise levels for avoiding stress and physiological effects. Noise types and levels that appear to increase stress and adverse physiological reactions in humans may also have similar consequences in birds.

2. *Damage to hearing from acoustic overexposure*: While many behavioral and physiological studies lack specificity, there are many definitive studies showing precise effects of intense noise on bird hearing and auditory structures. These extensive data show that birds are much more resistant to hearing loss and auditory damage from acoustic overexposure than are humans and other mammals. Traffic and construction noise, even at extreme levels, is unlikely to cause threshold shift, hearing loss, auditory damage, or damage to other organ systems in birds and, therefore, interim guidelines for hearing damage in birds from traffic and construction noise are probably not needed. Nevertheless, in rare instances where birds may be in close proximity to construction noise sources, such as impulse noise from pile driving, such noises may reach high enough levels to cause damage to auditory structures in birds.

3. *Masking of communication signals and other biologically relevant sounds*: Many laboratory masking studies precisely show the effects of continuous noise (including traffic noise) on sound detection in over a dozen species of birds. In a sense, these studies describe a "worst case" scenario because the noise is continuous and the myriad of short-term adaptive behavioral responses for mitigating the effects of noise are not available to the bird in a laboratory test situation. These masking studies led to an overall noise level guideline of around 60 A-weighted decibels (dBA) for continuous noise. A number of things have changed since this 60-dBA criterion was first suggested. Controlled laboratory and field studies have now shown that there are differences among bird species in signal-to-noise ratios at masked threshold. It is also now quite clear that probably all species of birds can use various short-term, adaptive behavioral responses in their natural environments to improve their signal-to-noise ratio. In other words, critical ratios vary across bird species by as much as 10 dB, strongly suggesting that acoustic communication in some species might be affected by an overall traffic and construction noise level of even less than 60 dBA. For some other bird species, communication between individuals, especially if they can employ short-term behavioral strategies for hearing in noise, might be unaffected at even higher levels of noise, perhaps approaching 70 dBA. These short-term behavioral adaptations include scanning (head turning), raising vocal output, and changing singing location. Each of these strategies alone can result in a significant gain in signal level or signal-to-noise ratio (under masking conditions) of about 10 dB, and birds can employ all three strategies simultaneously.

4. *Practical guidelines arising from masking studies*: The following are common sense, practical guidelines that emerge from basic hearing knowledge of birds and humans—specifically, the 6-decibel (dB) difference in masking (critical ratio) functions between typical bird and human listeners with normal hearing. 1) Humans can hear traffic noise, in a natural environment, at twice the distance from the roadway than can birds. In other words, if, in a natural environment, distant traffic noise is barely audible to humans, it is certainly inaudible to birds and will have no effect on any aspect of their acoustic behavior. 2) Humans can hear a bird singing against a background of noise at twice the distance than can the typical bird. This provides an informal estimate of maximum communication distance between two birds vocalizing against a background of continuous traffic noise. This works not only for the typical bird, but it is probably also valid for most species.

Table ES1. Recommended Interim Guidelines for Potential Effects from Different Noise Sources

Noise Source Type	Hearing Damage	TTS	Masking	Potential Behavioral/ Physiological Effects
Single Impulse (e.g., starter's pistol 6" from the ear	140 dBA[1]	NA[3]	NA[5]	Any audible component of traffic and construction noise has the potential of causing behavioral and/or physiological effects independent of any direct effects on the auditory system of PTS, TTS, or masking
Multiple Impulse (e.g., jack hammer, pile driver)	125 dBA[1]	NA[3]	Ambient dBA[6]	
Non-Strike Continuos (e.g., construction noise)	None[2]	93 dBA[4]	Ambient dBA[6]	
Traffic and Construction	None[2]	93 dBA[4]	Ambient dBA[6]	
Alarms (97 dB/100 ft)	None[2]	NA[2]	NA[7]	

TTS = temporary threshold shift
dBA = A-weighted decibel
PTS =permanent threshold shift
[1] Estimates based on bird data from Hashino et al. (1988) and other impulse noise exposure studies in small mammals.
[2] Noise levels from these sources do not reach levels capable of causing auditory damage and/or permanent threshold shift based on empirical data on hearing loss in birds from the laboratory.
[3] No data available on TTS in birds caused by impulsive sounds.
[4] Estimates based on study of TTS by continuous noise in the budgerigar and similar studies in small mammals.
[5] Cannot have masking to a single impulse.
[6] Conservative estimate based on addition of two uncorrelated noises. Above ambient noise levels, critical ratio data from 14 bird species, well-documented short-term behavioral adaptation strategies, and a background of ambient noise typical of a quiet suburban area would suggest noise guidelines in the range of 50–60 dBA.
[7] Alarms are non-continuous and, therefore, unlikely to cause masking effects.

These recommended guidelines for estimating the effects that traffic noise has on masking in birds are interim guidelines for the following reasons.

1. The interim guidelines are based on median data taken from masking studies done for a limited number of bird species. Thus, they represent the typical bird, based on the species studied. However, it is important to recall that different bird species can differ considerably in how they hear in the presence of noise; some have masked thresholds that approach those of humans, while others have masked thresholds that are 3–4 dB worse than thresholds for the typical bird presented here. Therefore, final noise guidelines will

require testing more species with appropriate experimental adjustment for the species in question.

2. Traffic noise characteristics are influenced by transmission through the environment as are the spectral, temporal, and intensive aspects of bird vocalizations through differences in excess attenuation. In other words, there is inherent variability in estimating the signal-to-noise ratio at the bird's ear in a natural environment. Traffic or construction noise varies from moment to moment. And the level of the signal reaching the receiver's i.e., the bird) ears will vary depending on the location of both the sender and the receiver. Final guidelines will require more data to quantify this variation.

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The Effects of Traffic Noise and Road Construction Noise on Birds

1. Introduction, Overview, Direction

Recent literature on the effects of noise in the environment has shown that the world is becoming a noisier place and that the effects of chronic noise exposure on terrestrial animals, including birds, could be significant (e.g., Barber *et al.*, 2010; Pijanowski *et al.*, 2011a; Pijanowski *et al.*, 2011b; Luther and Magnotti, 2014; Merchant *et al.*, 2015). Furthermore, with population increases and urbanization, traffic and road construction are increasing sources of environmental noise. However, because environmental noise is an inherently complex topic, it is important to define and isolate the sources of variation in determining when noise produced during the construction and operation of roadways has an impact on bird behavior and physiology.

The Endangered Species Act provides additional compelling motivation for understanding the effects of traffic and roadway construction noise on federally listed species. Effects of such noise may be nonexistent in certain circumstances, such as when the sound level of traffic and construction noise is below natural ambient noise levels, and effects may be insignificant in other circumstances, such as when such noise adds very little to existing ambient noise levels. In contrast, construction or traffic noise that adds substantially to natural ambient noise has the potential to produce a suite of significant short- and long-term behavioral and physiological changes in birds. These may include the following changes.

- Changes in the selection of foraging locations.
- Interference with acoustic communications between conspecifics.
- Failure to recognize other important biological signals such as sounds of predators and/or prey.
- Loss of hearing sensitivity temporarily or permanently.
- Increased stress and/or altered steroid hormone levels or other physiological effects.

Any of these effects could have long-term consequences and enduring impacts by interfering with breeding by individuals and populations, thereby threatening the survival of individuals or species.

This Guidance Document represent an updated version of the report entitled *The Effects of Highway Noise on Birds* (Dooling and Popper, 2007) prepared by the current authors. It should be noted that the vast majority of the research literature discussed in this document focuses on effects of traffic noise on birds, and there have been few, if any, studies on effects of roadway construction on birds. This is likely because roadway noise is far more prevalent and continuous than construction noise. Consequently, the models and analysis presented in this document focus on traffic noise.

A. Definitions

Several terms are used in this report. Some of these terms have multiple meanings and are defined herein. Other terms are defined in the glossary.

- **Construction Noise**: Noise produced during the construction of a roadway.
- **Effects**: any response by birds to traffic and construction noise. This definition does not invoke or imply regulatory definitions of "effect" as found in any law or regulation affecting birds.
- **Roadway**: Any paved road on which there is vehicular traffic.
- **Traffic Noise**: Noise produced by vehicles on any paved roadway, ranging from highways to single-lane streets.

B. Organization and Purpose of This Guidance Document

Sections 2 and 3 of this Guidance Document discuss bird audition, including how and what birds hear and how environmental noise can generally affect the auditory system and hearing. This is followed by Section 4, which discusses the effects of traffic and construction noise on birds, the challenges in surveying what is known about the effects of traffic and construction noise on birds, and the scientific literature on the topic. Section 5 summarizes the different classes of effects of noise on birds. Finally, Section 6 poses a first set of *interim* criteria to protect birds from traffic and construction noise. For readers interested in additional information, Appendix D discusses fundamentals of traffic noise (prepared by ICF Jones and Stokes), Appendix E presents a review of the older literature from the 2007 report, and Appendix F describes recommendations for critical future research that the authors suggest would enhance overall understanding of effects of traffic noise on birds.

The purpose of this Guidance Document is two-fold. First, it critically discusses what is known about the effects of highway construction and traffic noise on birds, with emphasis on the best available science. Generally, the reviewed literature has been directed at assessing and mitigating the impacts of noise produced by highway construction and operation on birds. This Guidance Document shows that there are still major gaps in this body of literature and very few firm conclusions, although there has been a substantial increase in knowledge since the first report (Dooling and Popper, 2007). As a Guidance Document should always reflect recent changes in the science, Appendix F points to areas for future research that would substantially enhance our future understanding of traffic noise on birds.

Second, this Guidance Document suggests *interim* compliance guidelines and a science-based approach, using human and avian data from both the laboratory and the field, to address potential impacts of noise on bird species. In areas such as hearing and masking of sounds as a result of noise, rigorous data are available from a wide range of species so that it is reasonable to extrapolate the effects on federally listed species. Such guidelines are done in coordination and consultation with compliance protocols for the federal Endangered Species Act.

C. Analysis of United States Fish and Wildlife Service (2006) Report

On July 26, 2006, the Arcata Fish and Wildlife Service Office (AFWO) of the U. S. Fish and Wildlife Service (FWS) issued guidance for estimating the effects of auditory and visual disturbance to northern spotted owls (*Strix occidentalis caurina*) and marbled murrelets (*Brachyramphu marmoratus*) in Northwestern California (AFWO, 2006).[2] These two species live

[2] http://goo.gl/3FLFCA

a rather solitary lifestyle and are expected to be particularly sensitive to noise disturbance. The purpose of the FWS guidance was to promote consistent and reasonable determinations of potential effects on either species that could result from elevated human-generated sounds or human activities in close proximity to nests during the breeding season. FWS acknowledged that its report is to be viewed as a living document subject to continued, ongoing revision, and improvement as additional data and experience are acquired.

The FWS document provides excellent guidance as to how a person in the field should make determinations with regard to the potential effects of construction and traffic noise on these two avian species, especially with regard to harassment.[3] This guidance is particularly valuable because it takes into consideration critical variables and tries to integrate them into a simple practical model. These variables include those listed below.

- Types of sound sources.
- Distances from the sound sources to the birds.
- Level of ambient noise in the environment.
- Levels of anthropogenic (human-generated) noise in the environment.
- Sound-modifying features in the environment.
- Visual cues correlated with the noise.
- The hearing sensitivity of the bird.

The FWS report provides a worthwhile potential strategy for estimating particular kinds of noise effects on these birds; however, the report has several limitations in terms of its applicability to other species. First, it is based on two relatively non-social species and does not address the kinds of effects that may be relevant for more gregarious species that flock and engage in continuous vocal communication with conspecifics.

Second, as discussed below, there are substantial differences between species in the ability to hear in noisy environments. As a consequence, one noise level is not likely to affect all species in the same way since some species will hear a particular level of sound and others will not due to their overall hearing sensitivity.

Third, how a bird responds to and integrates acoustic and visual stimuli in different contexts (e.g., breeding season or brooding) is likely to have a profound effect on whether harassment occurs. For example, very low level sounds bearing some resemblance to the sounds of a natural predator are likely to be far more important to the bird than other sounds of equal sound level but with no history of signaling danger. Such experiential factors will undoubtedly vary significantly by species.

Finally, the noise levels discussed in the FWS guidance are geared toward those that result in harassment or flushing from the roost or nest. There are other effects, such as masking of communication signals, that are also very important for species that must learn their vocalizations

[3] The Act's implementing regulations further define harass as "… an intentional or negligent act or omission which creates the likelihood of injury to wildlife by annoying it to such an extent as to significantly disrupt normal behavioral patterns which include, but are not limited to, breeding, feeding or sheltering" [50 CFR §17.3]. (Taken verbatim from p.4 of FWS (2006) report.)

and are engaged in continuous vocal communication with conspecifics throughout their lifetime, that are not considered in the FWS document.

Despite these caveats, the FWS report, together with information reviewed in this Guidance Document, may have value in helping reach a decision metric on possible effects of traffic and construction noise on birds. Moreover, the specific recommendations made in the FWS guidance report, while not fully applicable to situations involving continuous traffic and construction noise, represent a thoughtful approach to identifying and quantifying some of major variables for consideration.

D. Literature Surveyed in this Guidance Document

The material presented in this Guidance Document is based on a careful evaluation of technical reports and peer-reviewed articles, much of which is discussed in Section 4. The scientific approach and analysis used in each study differs, and so extrapolation between the studies, and especially those done in different locations or by different groups of investigators, is difficult and must be done with considerable caution.

In addition to primary peer-reviewed literature, this Guidance Document also cites a number of reviews covering various aspects of the issues considered here. These reviews, even if they have gone through appropriate peer review, often reflect the opinions and biases of the authors based on their analysis of the original material from peer-reviewed research articles.

Finally, wherever possible, this Guidance Document incorporates new material that has been produced since the authors' original review (Dooling and Popper, 2007). Taken together, the previously reviewed literature (see Appendix E) and the more recent literature significantly inform the conclusions and recommendations in this Guidance Document.

E. Metrics and Terminology

This Guidance Document contains a number of acoustic and biological terms. To facilitate understanding of terminology, most of the terms are defined in the glossary in Appendix A. Appendix D discusses fundamentals of traffic noise.[4] Those unfamiliar with fundamental concepts relating to traffic noise are advised to review information published by the California Department of Transportation (Caltrans) on the topic of highway traffic noise. This includes the Caltrans Traffic Noise Analysis Protocol (Protocol) (Caltrans, 2011),[5] the Technical Noise Supplement to Protocol (Caltrans 2013), and Caltrans online noise training.[6]

It is also important to define what is meant by "behavior" in this Guidance Document because the word is used for a wide range of activities, and usage also varies between different authors. For example, the term may be used to refer to the complex interaction of signals and rituals that animals use during mating or may also be used to refer to the movements of animals from one feeding

[4] Material in Appendix D was prepared by Caltrans and not by the authors of this report.
[5] http://www.dot.ca.gov/hq/env/noise/pub/ca_tnap_may2011.pdf
[6] http://www.dot.ca.gov/hq/env/noise/training_license.htm.

ground to another. In the context of this Guidance Document, "behavior" is used in its broadest possible sense unless otherwise qualified

F. Typical Roadway Operational and Construction Noise Levels

Traffic noise produced by vehicles traveling on a highway is a function of the traffic volume, vehicle mix, vehicle speed, and pavement type. For example, Table 1 summarizes typical traffic conditions for several typical highway configurations.

Table 1. Typical Highway Conditions

Number of Lanes	Highway Type	Worst Hour Traffic Volume	Speed	Heavy Truck %[!]
2	Highway	3,000	55 mph	2%
4	Highway	6,000	65 mph	2%
6	Freeway	12,000	65 mph	6%
8	Freeway	16,000	65 mph	8%

[!] Truck percentages can vary widely depending on the proximity of a roadway to commercial uses and truck routes. The truck percentages shown here are generally conservative for the roadway construction shown.

A considerable amount of work has enabled traffic engineers to model noise levels expected under various traffic conditions, road types, and vehicle speeds. Figure 1 shows traffic noise levels at various distances (in feet) from the roadway as predicted by the Federal Highway Administration (FHWA) Traffic Noise Model[7] (TNM) version 2.5 for each traffic condition in Table 1. Neutral atmospheric conditions (no inversion, moderate temperature, and wind speed less than 11 miles per hour [mph]) and soft ground surface (lawn) assumptions as recommended by FHWA were used. Additional assumptions included that the roadway was undivided, had no median lanes, was the typical 12 foot (3.6 meters) wide, and had average pavement, dry conditions, and moderate temperatures, with wind speed below 11 mph (17.7 kilometers per hour [km/h]).

With multiple lanes and a large number of vehicles, free-flowing traffic on a roadway acts like a line source. Geometric attenuation for a line source is 3 dB per doubling of distance. Additional attenuation resulting from ground absorption can add attenuation of about 1.5 dB per doubling of distance. Excess attenuation from ground effects, atmospheric absorption, wind, and temperature gradient effects, etc., are highly complex and can add attenuation over 5–10 dB per 100 m depending on the environment (e.g., Marten and Marler, 1977).

In contrast to the continuous noise produced by large volumes of traffic, noise produced by construction equipment is likely to be intermittent and impulsive (with very short rise-times), such as impact noise from a pile driver. Noise produced by construction equipment is a function of the type of equipment. Table 2 summarizes typical maximum noise levels at 50 feet (15.2 m) produced by typical construction equipment (see FHWA, 2006)[8]). In contrast to traffic noise, equipment used in roadway construction acts like a point source and will typically off at a rate of 6 dB per doubling of distance, although there is also likely to be additional attenuation that varies with the environment. Moreover, these are maximum noise levels which are not typically sustained over

[7] http://www.fhwa.dot.gov/environment/noise/construction_noise/rcnm/rcnm.pdf
[8] http://www.fhwa.dot.gov/environment/noise/construction_noise/rcnm/rcnm.pdf

long periods of time. Energy average sound levels can be developed based on utilization factors (FHWA, 2006).

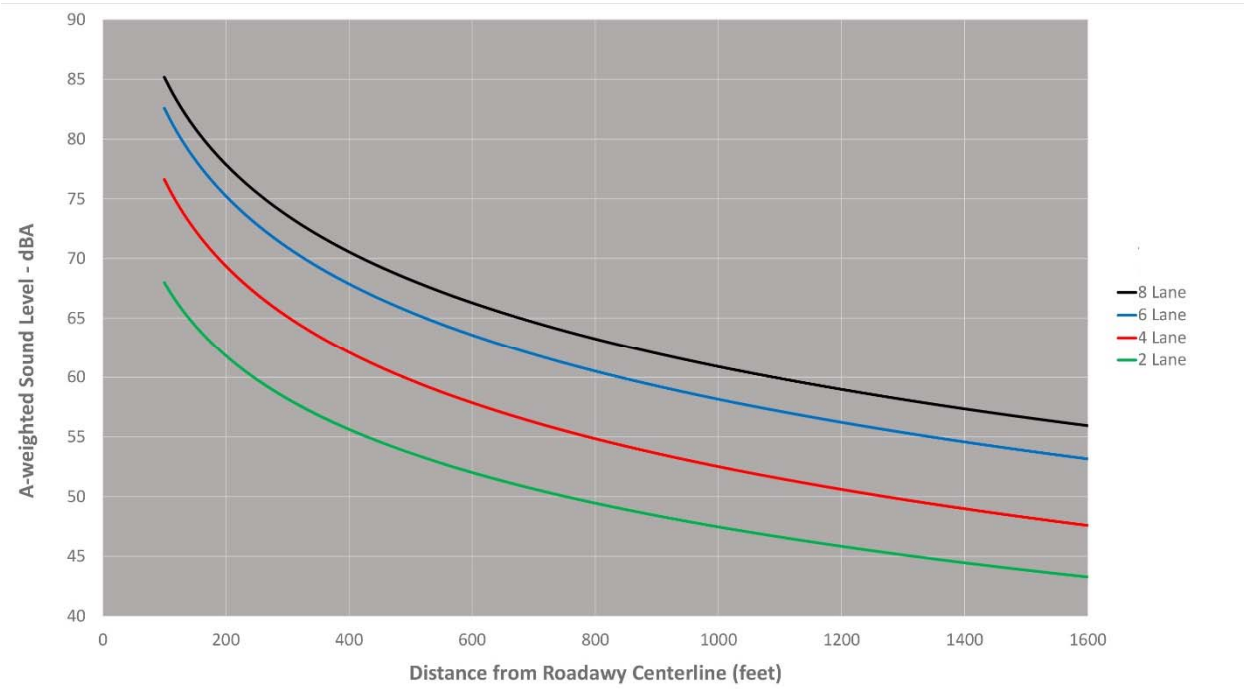

Figure 1. Typical Roadway Noise Levels as a Function of Distance
Data based on traffic conditions listed in Table 1
.

G. Relation between A-Weighted Sound Level in and Spectrum Level[9]

The noise levels described in Section 1.F for both traffic noise and construction noise are given in dBA[10] (see Appendix G for discussion of history of dBA for bird studies). The dBA scale for measuring sound levels takes into account the equal loudness contours of human hearing—that sounds at low frequencies and high frequencies presented at the same sound pressure level as intermediate frequencies are judged as softer than the sounds at intermediate frequencies. This scale is incorporated in most sound level meters and is thus convenient for the person doing the measurements. It may not always the most accurate measure for determining the effects of noise on bird hearing, however, because birds are even less sensitive to sound below 1 kHz than are humans, and birds have extremely poor hearing at frequencies about 10 kHz. Thus, the most relevant measure of noise for estimating the masking effects of noise on bird hearing is the spectrum level (the intensity level of a sound within a 1 hertz (Hz) band) in the frequency region where birds vocalize most and hear best—typically around 2–5 kHz.

Traffic noise and non-impact construction noise often show a sloping spectrum (Figure 2) with less energy in the region of 2–4 kHz than at lower frequencies. Thus, estimating the spectrum level

[9] Note that this Guidance Document does not include a direct discussion of the idea of 60 dBA that has been found in much of the earlier literature. A history of the use of 60 dBA is found in Appendix G.
[10] For a detailed discussion of dBA see: https://en.wikipedia.org/wiki/A-weighting

in the region of 2–4 kHz from an overall dBA level could overestimate the energy in the region of 2–4 kHz. On the other hand, traffic noise still has a considerable amount of energy around 1 kHz, and this band of energy contributes significantly to the overall dBA level actually resulting in a significant underestimate of the noise level actually in the 2–4 kHz bands that contain most bird vocalizations. Thus, in many cases, the overall level of the noise measured as dBA does not provide an accurate estimate of the noise level in the frequency region where birds communicate. Depending on the overall spectrum of the noise, it could underestimate, or more often overestimate, the masking effects of traffic noise on hearing and vocal communication in birds. In Figure 2, for instance, the overall level of noise is 84 dB (83 dB measured on the A scale) and this value is almost entirely accounted for by the energy in the octave band around 1 kHz. The level of noise in the frequency region that birds use for acoustic communication is much less, at around 60–65 dB.

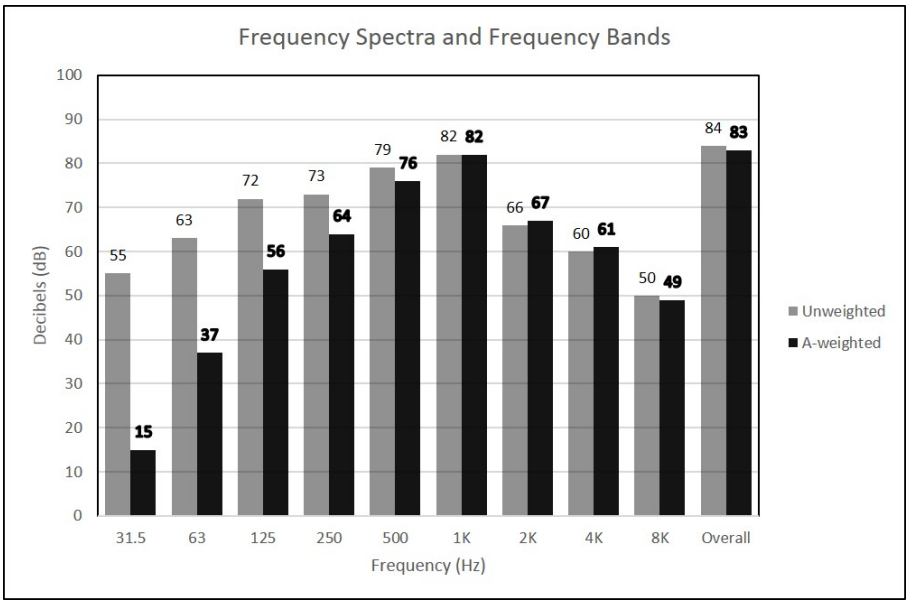

Figure 2: Caltrans Traffic Noise Spectra Showing Differences in Unweighted and Weighted Spectra and Overall Levels[11]

For traffic and construction noises, measuring overall sound levels in in dBA is likely to overestimate the effects of traffic and construction noise on communication in birds. A more accurate estimate would be obtained with measures of the sound pressure level in the octave bands at 2 kHz and 4 kHz From these two measurements, given the characteristics of traffic and construction noise, reasonably accurate estimates of spectrum levels can be obtained for the critical frequency range in which birds communicate and from these spectrum levels, decisions can be made about whether the noise will interfere with vocal communication. At 2.0 kHz, the spectrum level is roughly 33 dB less than the octave band level; at 4.0 kHz, the spectrum level is about 36 dB less than the octave band level.

2. The Bird Ear and Hearing

[11] Figure from: http://www.dot.ca.gov/hq/env/noise/online_training_module1/slides/slide50.htm

In order to appreciate the potential effects of traffic and construction noise on bird hearing, it is important to have some understanding of the bird ear and the basic hearing capabilities of birds both in quiet and in high noise settings (Dooling *et al.*, 2000a). It is also worthwhile to appreciate why birds, or any animals (including humans) hear, and why hearing may have evolved. In the case of many animals, especially birds and humans, hearing is closely related to acoustic communication (Dooling, 1982; Dooling *et al.*, 1992). Indeed, birds, more than most any vertebrate group other than primates, make use of a rich array of sounds for communicating, finding mates, expressing territorial occupation, and numerous other social behaviors.

Table 2: Construction Equipment Noise Emission Levels (greatest-to-least)[12]

Equipment	Typical L_{max} at 50 feet (15.2 m) from Source (dBA, Slow)
Pile Driver (Impact)	95
Vibratory Pile Driver	95
Rock Drill	85
Paver	85
Scraper	85
Crane	85
Jack Hammer	85
Concrete Mixer Truck	85
Dozer	85
Grader	85
Jackhammer	85
Pneumatic Tool	85
Crane	85
Chain Saw	85
Roller	85
Tractor	84
Concrete Pump Truck	82
Generator	82
Compactor (ground)	80
Compressor (Air)	80
Backhoe	80
Vibratory Concrete Mixer	80
Pumps	77

Source: Federal Highway Administration 2006. Table 1. http://goo.gl/PXltyy

Birds, as with humans and other animals, also use hearing to learn about their overall environments. Bregman (1990) refers to this as the "acoustic scene." This acoustic scene is the array of sounds in the environment, not just vocalizations, which may arise from biological or non-biological sources, such as predators moving through the environment or the wind moving through trees. This acoustic scene covers an area all around an animal, and it is just as rich at night as

[12] http://www.fhwa.dot.gov/environment/noise/construction_noise/rcnm/rcnm00.cfm

during the day when animals can use vision. The acoustic scene tells an animal a great deal about its extended environment. So, while this Guidance Document focus on the effect of noise on communication signals, it is important to also realize that other aspects of the animal's acoustic scene are also affected.

The bird ear and bird hearing has been well described over the years (e.g., Dooling *et al.*, 2000a; Gleich and Manley, 2000; Saunders *et al.*, 2000; Saunders and Henry, 2014). It consists of an external membrane (tympanic membrane), a middle ear (Saunders *et al.*, 2000; Saunders and Henry, 2014), and an inner ear (Gleich and Manley, 2000; Saunders and Henry, 2014). There is no external structure that resembles the mammalian outer ear flap, or pinna (except in owls). Instead, the tympanic membrane is the outermost covering of the middle ear.

The avian inner ear is similar to that of most vertebrates in that is has three semicircular canals to determine angular acceleration of the head and three otolith organs to detect motions of the head relative to gravity. In addition, birds have a cochlear duct that contains a basilar papilla upon which sit the sensitive sensory hair cells used for hearing. However, the basilar papilla is shorter and rather different in structure than that found in mammals (Tanaka and Smith, 1978; Smith, 1985; Gleich and Manley, 2000; Manley, 2000) and the differences may, to a degree, account for the much narrower range of frequencies detected by birds as compared to mammals.

Another factor that probably limits the frequency range over which birds hear is the presence of a single-bone middle ear rather than the three-bone middle ears (malleus, incus, stapes) that are characteristic of mammals (Manley, 2010). It has been suggested that the single columella in place of the three ear bones found in mammals is what limits hearing in most avian species to not much more than 10 kHz (Saunders *et al.*, 2000; Manley, 2010).

A. Behavioral Measures of Avian Hearing—the Audiogram

The minimum sound pressure that can be detected at frequencies throughout an animal's range of hearing defines the audiogram, or audibility curve.[13] This is the most basic measure of hearing and one most people are familiar with from having their own hearing tested. Over the past 50 years, behavioral audibility curves have been collected for about 39 species of birds, and this database can be extended by another 10 species of birds by including data from physiological recordings (Appendix B, also see Fay, 1988). These data are fit with a polynomial function to provide a continuous curve describing the minimum audible sound pressure over the range of hearing for a particular species.

Figure 3 shows the median audiogram based on the species in Appendix B. For animals, and sometimes for humans, the audiogram is measured in a sound attenuated room (an audiometric test chamber) so that the background noise is minimized and there is no interference by other sounds (i.e., masking). Thus the audiogram represents an ideal detection threshold that is rarely, if ever, attained in the real world, which always has some measurable amount of background noise.

[13] This is a measure of hearing "threshold." It should be noted that the threshold (the lowest sound detectable at a given frequency) is not a fixed value. There are slight variations from animal to animal and larger differences across species. Testing conditions and context can also play a role. Typically, the "threshold" is a statistical measure indicating the lowest sound pressure level that an animal can detect 50% of the time.

Audiograms are often described and compared on several features, such as the softest sound that can be heard (often referred to as best sensitivity or lowest intensity), the frequency at which hearing is best (best frequency—the frequency at which the subject can hear the softest sound), the bandwidth (the width of the audiogram to the point where it is raised by 30 dB on either side of the best frequency), lowest intensity (at the best frequency), and the low and high frequency limits of hearing (the frequencies at which thresholds are 30 dB above the best intensity) for both birds and humans. Interestingly, compared to species in other vertebrate groups, there is not wide variation in hearing sensitivity between different bird species. This suggests that the recommendations in this Guidance Document apply to most birds.

Generally, birds hear best at frequencies between about 1 and 5 kHz (Figure 3), with absolute (best) sensitivity often approaching 0–10 dB SPL[14] at the most sensitive frequency, which is usually in the region of 2–4 kHz (Dooling, 1980; 1982; 1992; Dooling *et al.*, 2000b). Nocturnal predators, such as most owls, can generally detect much softer sounds than can either Passeriformes (e.g., songbirds, such as sparrows, canaries, starlings, finches) or other non-Passeriformes (e.g., chickens, turkeys, pigeons, parrots, owls) over their entire range of hearing, sometimes with levels as low as -10 to -15 dB SPL. Passeriformes also tend to have better hearing at high frequencies than non-Passeriformes, while non-Passeriformes can detect softer signals at low frequencies than do Passeriformes. This difference is usually on the order of 5 to 10 dB. A recent correlative study of hearing characteristics (using the database in Appendix B) with several biological parameters confirms significant correlations among body weight, inner ear anatomy, and low- and high-frequency hearing in birds, with the exception of owls (Gleich *et al.*, 2005). Simply put, large birds hear better at low frequencies and small birds hear better at high frequencies. On average, however, the frequency range available to the typical bird for long distance vocal communication extends, at best, from about 1 to 4 kHz, the region of best sensitivity.

B. The Hearing Range and Vocalization Spectrum of Birds

Almost all avian species rely heavily on acoustic communication for species and individual recognition, mate selection, territorial defense, and other social activities. Studies of bird hearing have long shown a strong correlation between the range of hearing in birds and the frequency spectrum of bird vocalizations (Konishi, 1969; Dooling, 1980; 1982). That is, with the exception of some nocturnal predators such as barn owls, birds typically hear best in the spectral region of their species-specific vocalizations. Barn owls hear better at higher frequencies than do most other bird species because they have evolved to use high frequency cues to localize their prey in darkness. The importance of the general observation of a close match between hearing thresholds and vocalizations is that concerns over the effects of masking or hearing damage from noise should focus attention on the critical frequency region of about 1–6 kHz—the spectral region used for acoustic communication in birds (Dooling, 1982).

[14] SPL, or sound pressure level, is a widely used expression of the sound pressure using the decibel (dB) scale and the standard reference pressures 20 µPa for air.

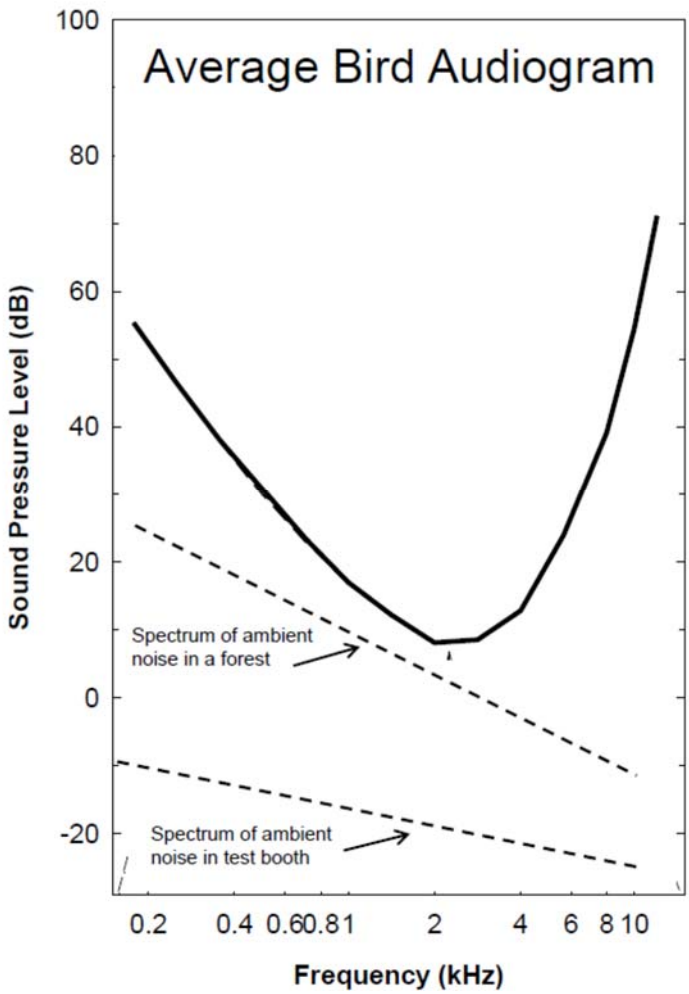

Figure 3: Bird Hearing Thresholds
Median bird hearing thresholds from 49 bird species (Appendix B measured behaviorally and physiologically in the free field in the quiet (solid line). The typical bird hears less well than humans and over a narrower bandwidth. Dotted lines show typical spectrum levels of the background noise in a double-walled acoustic isolation testing chamber and the spectrum level of ambient noise that a bird might encounter in a typical forest environment. An ambient noise spectrum level at least 20 dB below the audiogram will have no effect on hearing thresholds (i.e., no masking). An ambient noise level less than 20 dB below the audiogram thresholds, which is the case in almost all natural environments, will raise the animal's thresholds (i.e., cause masking).

C. The Hearing Capabilities of Nestlings

Less is known about hearing in nestlings and young birds as compared to sexually mature birds. However, a limited amount of data from young songbirds and parrots suggest that the auditory system of altricial birds (i.e., birds that are in an undeveloped stage at hatching in the nest and require care and feeding from parents[15]) does not function well at hatching. Auditory Brainstem Response (ABR, a type of physiological recording) studies of budgerigars[16] (*Melopsittacus undulatus*) and canaries (*Serinus canaria domestica*) indicate that hearing thresholds during the

[15] Altricial birds include all Passeriformes (songbirds). Altricial birds hatch with their eyes closed and with few, if any, feathers. In contract, precocial birds hatch with eyes open and are generally ready to leave the nest within two days of hatching—see: http://www.stanford.edu/group/stanfordbirds/text/essays/Precocial_and_Altricial.html
[16] Also known as a parakeet.

first two weeks after hatching of altricial birds are 30–40 dB higher than hearing thresholds of adults By the time nestlings are 20–30 days old and just getting ready to leave the nest; however, hearing thresholds as measured by the ABR approach adult levels of sensitivity (Brittan-Powell and Dooling, 2004).

Hearing thresholds in young birds and nestlings in the presence of noise have not yet been measured. While it is unlikely that nestlings can hear better in noise than adults, the fact that this is a critical stage in vocal development means that any additional noise, as from construction or traffic, may affect a bird's ability to acquire and develop its species-typical vocalizations. Recent laboratory work in zebra finches has now confirmed this suspicion (Potvin and MacDougall-Shackleton, 2015).

3. General Principles of the Effects of Noise on Birds

There are four general overlapping categories of construction and traffic noise effects on birds: permanent threshold shift (PTS—permanent hearing loss), temporary threshold shift (TTS—temporary hearing loss which recovers over a period of minutes to days from the end of noise exposure), masking, and other physiological and behavioral responses. The actual auditory effect that is encountered depends upon the level of noise arriving at the bird's ear, which is highly correlated with the proximity of the bird(s) to the noise source (Figure 4, Table 3).The existing scientific literature provides a considerable amount of data that can be used to define the boundaries between these categories of effects e.g., Dooling *et al.*, 2008; Salvi *et al.*, 2008; Saunders and Salvi, 2008).
Based on Figure 4, it is possible to generalize on the potential effects of highway and construction noise on birds, depending on their distance from the source. The distance of each zone is arbitrary and depends on the level of the source. Thus, if the level of the source is very high, each zone will be large, whereas if the sound level at the source is low, the distances between the zones will be smaller. Regardless, as is shown, these zones no doubt overlap with regard to potential effects.

a. Zone 1: If a bird is in this region, it is close to the noise source such that traffic and construction noise can *potentially* result in all four effects—permanent threshold shift, temporary threshold shift, masking, and other behavioral and/or physiological effects. Laboratory evidence shows that continuous noise levels above 110 dBA SPL lasting over 12–24 hours, or a single impulsive noise over 140 dB SPL (125 dB SPL for multiple blasts), can cause damage and loss of inner ear sensory hair cells resulting in a large initial threshold shift, followed by a small (~10–15 dB) lingering threshold shift even after all hair cells have been regenerated (Saunders and Dooling, 1974; Dooling and Saunders, 1975; Dooling *et al.*, 2008).

b. Zone 2: At greater distances from the roadway, starting where the received noise levels fall below 110 dBA continuous exposure, hearing loss and permanent threshold shift are unlikely to occur. However, continuous traffic and construction noise above 93 dBA SPL might still temporarily elevate a bird's threshold, mask important communication signals, and possibly lead to other behavioral and/or physiological effects.

c. Zone 3: At even greater distances from the roadway, where the spectrum level of the noise is still at or above the natural ambient noise level, masking of communication signals from this added noise may occur. This, in turn, may also result in other behavioral and/or physiological effects.

d. Zone 4: Once the level of traffic and construction noise falls below ambient noise levels in the critical frequencies for communication, masking of communication signals is no longer an issue. However, faintly heard sounds, such as the low rumble of a truck, or an alarm from a construction site, may still lead to a chronic state of increased arousal and, thus, lead to other behavioral and/or physiological effects.

e. Beyond Zone 4: At this boundary, the energy in traffic noise and construction noise at all frequencies is completely inaudible (i.e., falls below the level of the ambient noise). The bird cannot hear this noise and, thus, the noise has no effects of any kind on the bird.

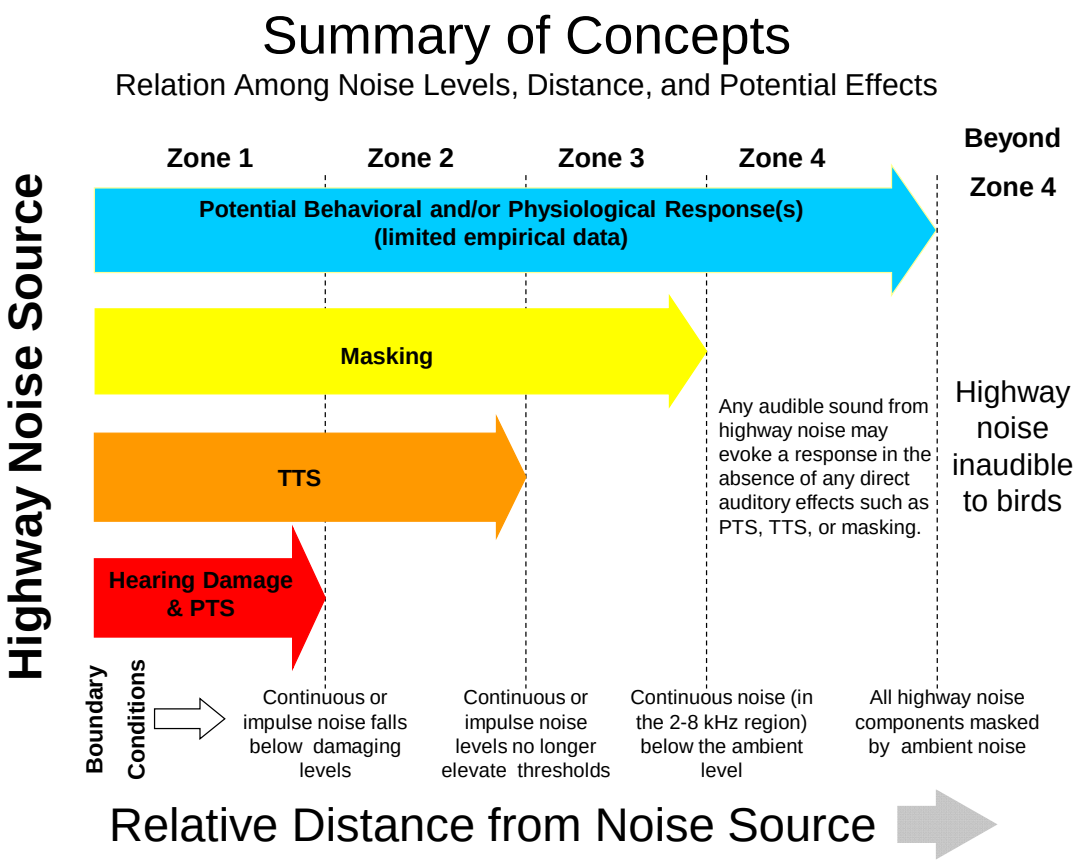

Figure 4: Potential Effects of Traffic and Construction Noise on Birds
Categories of traffic and construction noise effects on birds with distance from the source. Zone 1 is closest to the source while Zone 4 is furthest away. Sound level decreases further from the source. Note that the actual distances for the Zones ae not given since that would depend on the source sound level, hearing sensitivity of the receiver, and the propagation distance from the source to the receiver. See text for detailed discussion.

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e. Beyond Zone 4: At this boundary, the energy in traffic noise and construction noise at all frequencies is completely inaudible (i.e., falls below the level of the ambient noise). The bird cannot hear this noise and, thus, the noise has no effects of any kind on the bird.

Before considering the effects on the auditory system of birds from traffic and construction noise, it is important to understand three facts about potential behavioral and physiological effects of traffic and construction noise. One is that these effects can occur alone or in combination with effects on the auditory system of birds. Second, behavioral and physiological effects may be less dependent on noise level and more dependent on environmental context and the salience of the traffic and construction noise component(s) to the bird. Third, in contrast to the effects of noise on the bird auditory system, there are fewer empirical data available on behavioral and physiological effects, and especially for those effects that occur alone, as in Zone

Table 3: Recommended Interim Guidelines for Potential Effects from Different Noise Sources				
Noise Source Type	**Hearing Damage**	**TTS**	**Masking**	**Potential Behavioral/ Physiological Effects**
Single Impulse (e.g., starter's pistol 6" from the ear	140 dBA[1]	NA[3]	NA[5]	Any audible component of traffic and construction noise has the potential of causing behavioral and/or physiological effects independent of any direct effects on the auditory system of PTS, TTS, or masking
Multiple Impulse (e.g., jack hammer, pile driver)	125 dBA[1]	NA[3]	ambient dBA[6]	
Non-Strike Continuos (e.g., construction noise)	None[2]	93 dBA[4]	ambient dBA[6]	
Traffic and Construction Noise	None[2]	93 dBA[4]	ambient dBA[6]	
Alarms (97 dB/100 ft)	None[2]	NA[2]	NA[6]	

[1] Estimates based on bird data from Hashino et al. (1988) and other impulse noise exposure studies in small mammals.
[2] Noise levels from these sources do not reach levels capable of causing auditory damage and/or permanent threshold shift based on empirical data on hearing loss in birds from the laboratory.
[3] No data available on TTS in birds caused by impulsive sounds.
[4] Estimates based on study of TTS by continuous noise in the budgerigar and similar studies in small mammals.
[5] Cannot have masking to a single impulse.
[6] Conservative estimate based on addition of two uncorrelated noises. Above ambient noise levels, critical ratio data from 14 bird species, well documented short term behavioral adaptation strategies, and a background of ambient noise typical of a quiet suburban area would suggest noise guidelines in the range of 50–60 dBA.
[7] Alarms are non-continuous and therefore unlikely to cause masking effects.

A. Effects of Noise on Hearing in Birds—Threshold Shift

Birds (as well as humans and other animals) show a shift in hearing sensitivity in response to sounds that are sufficiently long and/or intense. There are several recent reviews of the effects of trauma to the auditory system of birds (Dooling *et al.*, 2008; Salvi *et al.*, 2008; Saunders and Salvi, 2008). Taken together, the data show that birds can tolerate continuous (i.e., up to 72 hours) exposure to noises of up to received levels of 110 dBA without experiencing hearing damage or a significant permanent threshold shift.

Permanent Threshold Shift: A PTS occurs if the intensity and duration of the noise is sufficient to damage or kill the inner ear sensory hair cells or other structures in the inner ear. In birds, thee specific damage to sensory hair cells depends on the type, intensity, and duration of the acoustic trauma (reviewed in Cotanche, 1998). Since hearing depends on the function of these hair cells, their permanent loss in mammals, including humans, results in permanent hearing loss. However, since birds can regenerate damaged or destroyed sensory hair cells usually within a month, there can be substantial recovery of hearing, although there is often still a small, insignificant 10 dB threshold shift that remains permanent (Dooling and Saunders, 1974; Saunders and Dooling, 1974).

A number of comparative studies on hearing loss in birds are instructive in understanding important sources of variation on the effects of sound exposure on birds. For example, Japanese quail (*Coturnix coturnix japonica*) exposed to a 1.5 kHz octave band noise at 116 dB SPL for four hours showed hearing loss of up to 50 dB immediately following exposure (Niemiec *et al.*, 1994). Hearing loss was most severe at frequencies at and above 1.0 kHz, although there was considerable

variation between subjects. Hearing loss was accompanied by a significant loss of sensory hair cells in the basilar papilla. Nevertheless, hearing improved rapidly within the first week following exposure, and recovered to pre-exposure levels within 8–10 days. Damaged hair cells were observed up to 2 weeks post exposure, but there was little evidence of damage to hair cells at 5 weeks post-exposure. Similar patterns of threshold shifts and recoveries were seen after repeated exposures to noise, although recovery times increased with increasing exposure duration. The authors found there can be a return to normal sensitivity prior to complete regeneration of the sensory hair cells (Bennett *et al.*, 1994) suggesting birds do not need a full complement of hair cells for normal hearing.

Ryals and colleagues (1999) found that the amount of hearing loss and the time course of recovery varied considerably among different bird species, even with identical exposure and test conditions. In one study, Japanese quail and budgerigars were exposed to pure tones of 112–118 dB SPL for 12 hours, with the frequency of the sounds centered in the region of best hearing of each species. Quail showed much greater susceptibility to acoustic trauma than did budgerigars, and showed significantly larger threshold shifts and hair cell loss. Quail showed a threshold shift of 70 dB at 2.86 kHz at one day following over-exposure, and this hearing loss remained virtually unchanged for 8–9 days after exposure. Hearing began to improve by about 1 dB/day until recovery at day 50, at which time recovery reached asymptote. This left the quail with a permanent threshold shift of approximately 20 dB, which remained even 1 year following exposure. In contrast, budgerigars showed a threshold shift of about 35–40 dB and a much faster recovery than the quail. By thee days after exposure, budgerigars' thresholds had improved to within 10 dB of normal. In human hearing, elevated thresholds of 10 dB are still considered within the normal range.

In another experiment, budgerigars, canaries, and zebra finches were exposed to the same band pass noise (2–6 kHz) at 120 dBA SPL for 24 hours. Thresholds at 1.0 kHz were initially elevated by 10–30 dB but returned to within normal limits by about 10 days after exposure in all three species. Moreover, at 2.86 kHz, the center of the exposure band, all three species showed a 50 dB threshold shift. Recovery began immediately after the noise was terminated for canaries, while zebra finches recovered to within 10 dB of normal by about 30 days after exposure. However, thresholds remained elevated for 10 days before recovery begin to occur in budgerigars. By 50 days after exposure, thresholds for budgerigars still only recovered to about 20 dB above normal. Thus, in this experiment, there was significantly more rapid recovery in canaries and zebra finches than in budgerigars.

These comparative studies, and especially those by Ryals and her colleagues (Ryals and Rubel, 1985a, b; Ryals *et al.*, 1999), are important for understanding the effects of intense noise on hearing in birds. The Ryals et al. (1999) study showed that different species, tested under identical noise exposure and test conditions, all showed resistance to hearing damage from noise. In addition, these studies show that there is considerable variation among species in the amount of damage and the time-course of loss and recovery from acoustic trauma. Thus, concern over the effects of loud sounds on the ear and hearing is quite reasonable (McFadden and Saunders, 1989; Saunders *et al.*, 1991; Adler *et al.*, 1992; Adler *et al.*, 1993; Pugliano *et al.*, 1993; Saunders and Salvi, 1993). These studies suggest that, for birds, permanent hearing loss from traffic noise or construction noise is probably not a significant concern.

Temporary Threshold Shift: At continuous noise levels below 110 dBA down to about 93 dBA, birds may experience a temporary threshold shift (TTS) which lasts from seconds to days, depending on the intensity and duration of the noise to which the animal was exposed. In contrast to a PTS, hearing recovers completely from TTS to the level that it was before the exposure. Nevertheless, during this period of TTS the bird's hearing is temporarily impaired and this could affect a variety of auditory and vocal communication behaviors, including detection of predators, communication with young, auditory feedback, etc. There have been a number of studies quantifying the relation between noise exposure and temporary threshold shift in birds. Several of the most relevant studies are described below.

Budgerigars exposed to a narrow band of noise centered at 2 kHz for 72 hours at levels of 76–106 dB SPL showed maximum hearing losses at 2 kHz with a TTS ranging from 10–40 dB depending on the level of the noise to which the birds were exposed (Saunders and Dooling, 1974; Dooling, 1980) (Figure 5). Importantly, a PTS of 7–10 dB was observed only with the 106 dB exposure (Dooling, 1980). A 72-hour continuous exposure to a narrowband of noise at 106 dB would result in severe and permanent hearing loss in humans due to irrevocable damage to the sensory cells of the inner ear. TTSs in these birds also lasted less time than typically seen in mammals and were also restricted to a narrower range of frequencies (e.g., Luz and Hodge, 1971; Dooling, 1980; Henderson and Hamernik, 1986). The maximum threshold shift in budgerigars occurred at the exposure frequency (rather than at higher frequencies in mammals) and showed much less spread of threshold shift to other frequencies.

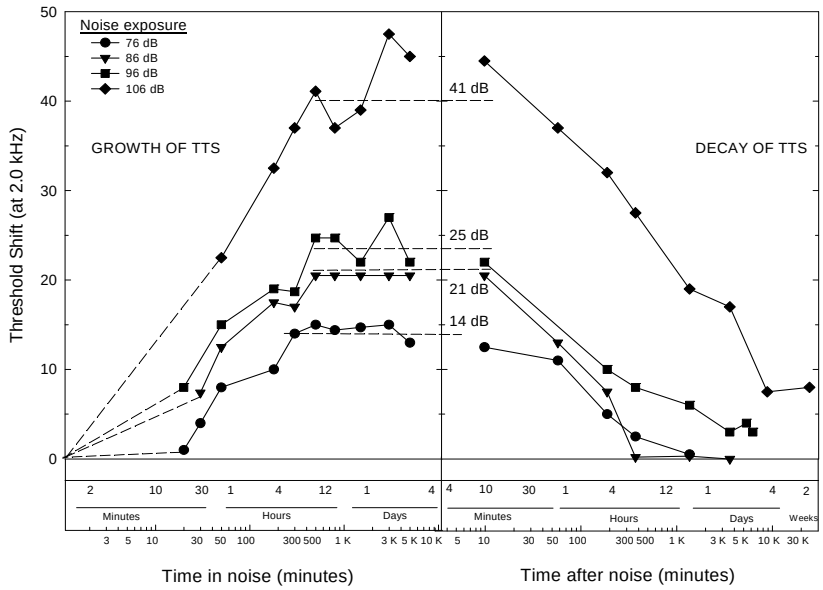

Figure 5: Threshold Shift in Birds Exposed to Noise
The growth and decay of threshold shift in four budgerigars exposed to four different levels of a one-third octave band of noise for 72 hours. Threshold shift reaches an asymptote (horizontal dashed line) after 12–24 hours regardless of the exposure level. Exposure to a 76 dB noise results in a threshold shift of 14 dB which recovers within a few hours following the termination of the noise. Exposure to a 106 dB noise, however, leads to longer recovery time and a permanent threshold due to damage to the inner ear (Dooling, 1982).

Finally, all the experiments described above were conducted with continuous noise, much as would be expected with dense traffic or continuous construction noise (Table 1, Figure 1). Impulse noises,

such as those produced by single pieces of construction equipment, are short, intermittent, high intensity, and have very fast rise times (Table 2).

Much less is known about the effects on avian hearing resulting from high-level impulse sounds as might be experienced in close proximity to construction equipment as compared to lower level, continuous noise as from traffic. There is a single report in the literature that exposed budgerigars to four 169 dB SPL blast impulses produced by starter pistol shots in close proximity (20 cm) to the bird. In contrast to results from a continuous noise exposure, this impulsive exposure initially caused more low frequency (~60 dB) than high frequency (~40 dB) hearing loss (Hashino *et al.*, 1988). Even from this extremely intense exposure, however, thresholds at 1 and 4 kHz (the frequencies at which budgerigars sing and hear best) returned to almost normal within 20 days following the exposure. At 500 Hz, there remained a permanent threshold shift of about 20 dB even 40 days after exposure. These results confirm that birds are resistant to permanent auditory damage and hearing loss from noise exposure, even following extraordinarily exposure to intense impulse noise.

B. Masking and the Characteristics of Noise

Masking is the interference of the detection of one sound by another. For example, two people in a room talking at a comfortable level can easily hear one another because the level of the speech signal arriving at the ear is sufficiently greater than the background noise. If the people are having the same conversation in a noisy restaurant, it may be much harder for them to hear one another because the level of the background noise approaches the level of the speech signal from their companion. This is an example of the masking of speech by speech. Moreover, masking can also occur from other kinds of noises that also have energy in the spectral region of speech (e.g., noisy fans, air conditioners, traffic noise).

The simplest kind of masking experiment is to measure the sound detection thresholds for pure tones (the signal) in the presence of a broadband noise (see Appendix A). The noise in such an experiment is usually described in terms of a spectrum level (i.e., sound energy per Hz) rather than the overall sound pressure level. The signal level in the case of a pure tone is, of course, simply the level of the tone in dB. Experiments on masking in birds (and other animals) show that at low- to mid-levels, it is the noise in the frequency region of a signal that is most important in masking the signal—not noise at more distant frequency regions (Dooling *et al.*, 2000b). It could be the case that if the masker energy is at a low to moderate level in a frequency range that does not overlap with that of the pure tone, there may be no change in threshold for the pure tone.[17]

Masking of signals by noises in the same frequency range is an important phenomenon to keep in mind when estimating the effects of different kinds of noises on hearing. Common experience shows that acoustic communication can be severely constrained if background noise is of a sufficient level.[18] Such noise decreases signal-to-noise-ratios and thereby restricts the range over which a signal produced by a bird can be heard by another bird. In simple terms, background noise

[17] The amount of masking depends primarily on the amount of energy in the masker in the frequency region surrounding the pure tone. This band of frequencies around the pure tone in which masking will still occur is called the "critical band."

[18] The exact level depends on many factors, including masker level and the hearing sensitivity of the species of concern.

makes it harder for an animal (including humans) to hear sounds of conspecifics or other sounds that may be biologically relevant. Otherwise said, it limits the organism's active acoustic space.

The masking case described above with a pure tone and broad band noise is very simple. In a natural setting, the situation is usually much more complex. The signal is rarely a pure tone, and the masker is rarely flat, broadband noise. Moreover, human work shows that it has been difficult to come up with a broadly acceptable definition of noise because of extreme variations in both the physical properties of noise and the perceptual preferences of listeners.[19] For humans, perhaps the broadest, most universally accepted definition is that noise is simply unwanted sound. This definition, however, is not useful in trying to predict the effects of masking on animal communication.

To make matters even more complex, noises can be continuous or intermittent, broadband or narrowband, or predictable or unpredictable in time or space. These noise characteristics determine the strategies that birds might employ to minimize the effects of noise on acoustic communication. Most laboratory studies measuring the effects of noise on signal detection (as described above) use continuous noises with precisely defined bandwidths, intensities, and spectral shapes. Because traffic noise on heavily traveled roads can approximate some of these features (e.g., relatively continuous, relatively constant spectrum and intensity), it increases the validity of using laboratory results to make predictions about how far away two birds can be in a natural setting and still hear one another in a background of traffic noise. In fact, for this purpose, laboratory masking studies define the worst case estimate of communication distance in the natural setting. This is because the animal being tested in the laboratory is in a fixed location with respect to the loudspeaker that is producing both the noise and the signal and head movement is restricted. Whenever these two conditions are not met, as is usually the case in a natural setting, the amount of masking from traffic noise is likely to be less, and sometimes considerably less, than predicted from signal-to-noise ratios measured in the laboratory.

C. Comparative Masking Effects in Birds—Critical Ratio

The ratio between the power in a pure tone at threshold and the power per Hz (the spectrum level) of the background noise is called the *critical ratio* (Fletcher, 1940). The masking principles discussed above that govern the critical ratio are shown schematically in Figure 6 (see also Figure 7). The critical ratio (left panel of Figure 6) is defined as the sound pressure level of a tone (when it is just masked) minus the spectrum level of the noise. In this case, the spectrum level of the noise is 40 dB SPL, and the level of a 3 kHz pure tone that can just be heard is 60 dB SPL, resulting in a critical ratio of 20 dB. Since it is noise in the spectral region of the tone that contributes most to the masking of the tone, measuring overall noise level over a very wide band of frequencies is not very useful unless the noise is flat and one can accurately estimate the level of noise around the signal. For a flat noise with an overall noise level of about 80 dBA, when measured across the whole band of noise, would have a spectrum level of 40 dB across the whole spectrum and in the region of the pure tone. When the noise is not flat, it is hard to calculate the spectrum level in the frequency region around 2–6 kHz—the frequency region that contains most of the energy in bird vocalizations.

[19] What is "noise" to one listener may be music to another, and vice versa.

Critical ratio data have now been obtained behaviorally for 14 species of birds, including songbirds (e.g., canary, sparrows, etc.), non-songbirds (e.g., budgerigars, pigeons), and some nocturnal predators (e.g., barn owl) (Dooling *et al.*, 2000b). Figure 7 shows the median critical ratio functions for the 14 species of birds (see Appendix C for these data) with corresponding values from the literature on tone masking by noise in human. There is species variation in bird critical ratios, with some birds approaching human levels of sensitivity and others being much worse than the median curve. However, the median function shows the typical pattern of approximately a 2–3 dB/octave increase in signal-to-noise ratio that has come to be characteristic of these functions in mammals, including humans (roughly a 3 dB/octave slope). The correlation between the increase in masking effectiveness and frequency is thought to be related to the mechanics of the peripheral auditory system (von Békésy, 1960; Greenwood, 1961a; b; Klump *et al.*, 1995).

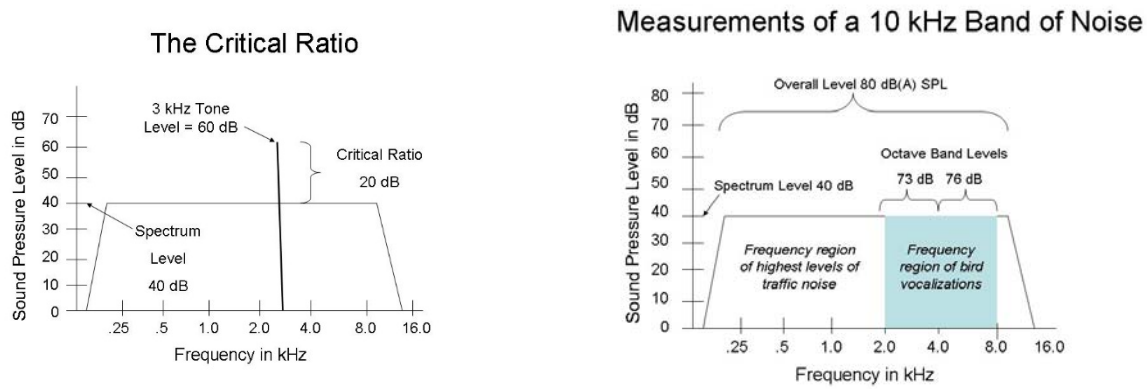

Figure 6: Avian Critical Ratios
(Left) Schematic representation of the critical ratio. A 60 dB tone at 3 kHz is just masked by a broad band noise with a spectrum level of 40 dB. The critical ratio is defined as the level of the tone minus the spectrum level of the noise. (Right) The relationship for overall sound pressure level, spectrum level, and octave band levels between 2 and 8 kHz for a flat broad band noise. The overall level of noise of 80 dBA is greater than the amount of noise falling in the octave band of 2–4 kHz (73 dB) and 4–8 kHz (76 dB). Much of the energy in traffic and construction noise falls in lower frequencies, while bird vocalizations fall in mid- to higher frequencies. Measuring noise that is in the spectral region of bird vocalizations is critical to understanding whether masking occurs because it is predominantly the noise in this spectral region that contributes to the masking.

In practical terms, this critical ratio curve describes the level in decibels above the spectrum level of the background noise that a sound (usually a pure tone or other narrow band sound) must be in order to be heard. For the typical bird, a pure tone (or tonal vocalization) in the region of 3 kHz must be at about 27 dB (± 3dB) above the spectrum level of noise in order to be detected. In fact, birds vary in their critical ratios from about 21 dB (budgerigar) to about 32 dB (canary) at 3 kHz. For the human, the same pure tone need only be about 21 dB above the spectrum level of noise to be heard—a difference of about 6 dB from the typical bird (Dooling and Popper, 2000).

These data raise two important issues. First, there is little variation in how humans with normal hearing are able to detect signals in noise. The same is true of animals within a species. However, there is considerable variation across species in how well organisms can hear in noise, including among different species of birds. As is the case with susceptibility to auditory damage from noise exposure, there is no way to tell from a bird's vocalizations, physical appearance, or behavior,

whether it hears well or less well in noise. Thus any complete model for predicting masking for a given species should use the species' critical ratio. The next best solution is to use the average or median values of all bird critical ratios.

Second, the difference in masked thresholds of 6 dB between humans and a "representative" bird with median masking thresholds for the 14 avian species studied has important implications for the detection of a point source of sound (e.g., a single vehicle, a piece of construction equipment, a bird singing, etc.) in a natural setting. Recall that sound pressure level decreases about 6 dB for a point source with every doubling of distance (by the inverse square law). What this means is that if a human listener can barely hear the sound of an automobile or a piece of construction equipment at 100 meters from the highway because of background ambient noise, the typical bird could not hear it at all. The bird would have to move twice as close to the highway (i.e., 50 meters) to barely hear the sound of an automobile. For a line source (e.g., a stream of traffic) which deceases at 3 dB/doubling of distance, this difference between birds and humans is a factor of 4.

Generally, since human auditory thresholds in quiet and in noise are about 6 dB better than that of the typical bird, this leads to the following two facts when conclusion on assessing the effect of noise on birds:

(1) When estimating whether a bird might be disturbed by hearing traffic or construction noise from a distant site, this 6 dB difference in masked thresholds means that if a human can barely hear traffic or construction noise from a distant site, a bird certainly cannot hear the noise and therefore can't be disturbed by it. The rule that "if a human can't hear it, a bird can't either" thus proves a handy rule of thumb for estimate whether a distant noise from construction equipment might be disturbing.

(2) However, when trying to estimate whether two birds can acoustically communicate against a background of traffic or construction noise, this 6 dB difference also means that the typical bird must be much closer to a singing bird to be able to hear it than does a human. So, if a human can barely hear a singing bird in the distance, the typical bird would not be able to hear it. In fact the bird would have to be even closer (i.e., half the distance) in order to hear the singing bird. In this case, human perceptual experience provides a dangerously poor estimate of whether two birds can hear one another against a background of traffic noise. It underestimates the effect of noise on communicating birds by over estimating the distance over which birds can communicate.

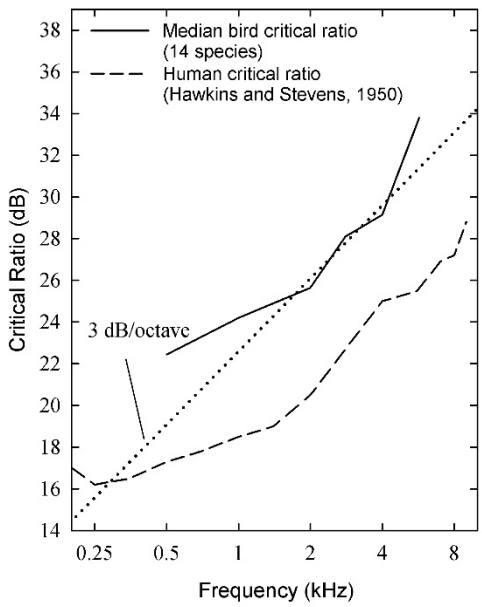

Figure 7: Critical Ratios in Birds and Humans

Median critical ratios for 14 birds (solid line) and the human (dashed line). Dotted line is a slope of 3 dB/octave. The critical ratio (s/n ratio) at threshold is about 6 dB greater in the typical bird compared to humans over the frequency range of 1–5 kHz (Dooling *et al.*, 2000b). These median critical ratios for birds represent the best available science of how birds hear in noise and can be used to predict how well birds can communicate in noise.

D. Understanding the Implications of Masking and Hearing in Noise

As discussed earlier, the audiogram represents the lowest sound pressure level (in dB) of pure tones throughout the range of hearing that can be detected in the quiet background of a test booth (see Figure 2). But since all hearing in natural settings is against a background of noise, the pure tone audiogram is not very useful for estimating what a bird can hear in a natural setting. In other words, in all environments, other than a quiet background of a test booth, ambient noise in the background has a large effect on what can be heard (i.e., the critical ratio). Therefore, the critical ratio (Figure 6) provides the metric for estimating the effects of noise on the audiogram because it shows the level (in dB) that a pure tone must be above the spectrum level of noise in order to be heard.

The realization that all hearing in natural settings are masked thresholds and that a signal, in order to be heard, must be a certain level above the noise, provides a way to estimate the effect a particular continuous noise on the hearing of the typical bird. In the case of the 84 dBA traffic noise illustrated in Figure 8, there is a large masking effect from traffic noise at low and mid frequencies of the bird audiogram but less at high frequencies. Birds living in city environments tend to have higher pitched vocalizations than their rural counterparts because there is less masking from traffic noise at higher frequencies in rural environments.

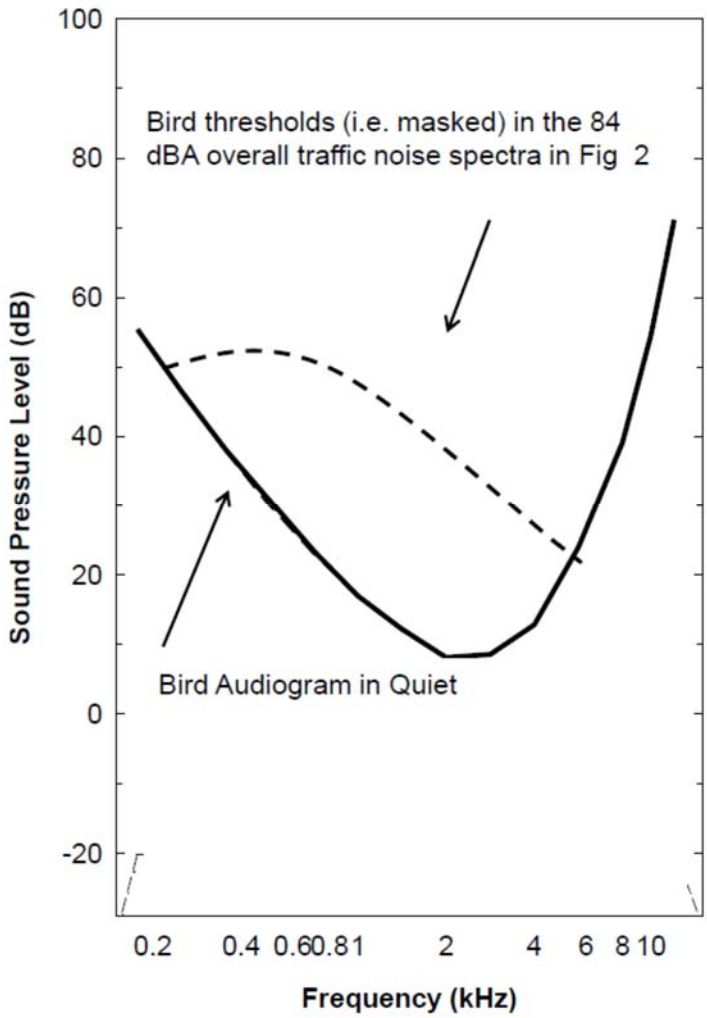

Figure 8: The Effects of Traffic Noise of 84 dBA on Hearing Thresholds of the Typical Bird
The effects of traffic noise illustrated earlier in Figure 2 raises a bird's threshold. The solid line shows the auditory thresholds (audiogram) in the quiet. The dashed line above the audiogram shows elevated thresholds due to masking by traffic noise at a level of 84 dBA. Thresholds are considerably elevated at low- to mid-frequencies.

4. Effects of Traffic and Construction Noise on Birds—A Review of Relevant Literature

A. Overview

Reviewing effects of traffic noise on birds has been challenging in several ways as; it is difficult to find an effective way to evaluate information from very diverse perspectives to arrive at a useful predictive tool. One challenge is separating the effects of noise on birds from the effects of other variables (usually visual, but possibly vibratory or olfactory) that may occur along with the noise. Another challenge is in is applying findings from well-controlled laboratory studies involving a few species to the effects of noise exposure on birds in their natural environments. Under controlled circumstances in the laboratory, hearing capabilities can be measured to a precise degree. As mentioned above, these measures, when taken to the field, represent a worst case in terms of predicting the effects of noise on birds. This is because in laboratory studies, the noise is

presented continuously, the signal and the noise are coming from the same location, and any other environmental cues ordinarily associated with the signal (e.g., visual cues) or the noise that might aid auditory perception of important biological signals in a natural setting are not present. Wild animals use an array of short term and long term strategies for counteracting the effects of noise in more natural environments, as described later. These are similar to the behaviors that humans employ in trying to hear and communicate in a noisy environment such as turning the head, raising the voice, moving closer to the source, etc.

Studies and reviews of the effects of traffic and construction noise on birds are often included in a broader literature on the effects on birds of other noise sources, most notably those produced by aircraft (airplane or helicopter) over-flight (e.g., Brown, 1990). Such studies sometimes provide insight into the effects of noise on breeding biology (e.g., Bunnell *et al.*, 1981), survival of eggs and young birds (Burger, 1983; Leonard and Horn, 2008), and non-auditory physiological effects. A number of these papers might also serve as more controlled experimental studies where the effects of noise on birds could be isolated and understood, and such studies may provide guidance for the type(s) of studies that are needed in order to better understand the effects of traffic and construction noise on birds.

At the same time, the characteristics of noise from aircraft is sufficiently different from that produced by traffic that extrapolation from one set of response data to the other is very difficult (Stansfeld *et al.*, 2005; Murphy and King, 2014) and perhaps should not be done at all. These differences include sound level and temporal distribution. Generally, at similar distances from the source, aircraft noise is far more intense than noise from roadways. Moreover, exposure to aircraft noise is almost always intermittent, whereas traffic noise can often be characterized and modeled as a continuous, lower level noise source. Birds respond to such differences in sounds in different ways; therefore, it becomes questionable whether it is possible to extrapolate between sound sources in trying to assess the effects of traffic noise on birds.

There is considerable evidence that road noise can contribute to stress and alter human physiology in many ways (Miller, 1974; Öhrström and Rylander, 1982; Öhrström and Björkman, 1983; Ouis, 2001; Le Prell *et al.*, 2012; Murphy and King, 2014). While caution should rule in the extrapolation of data from humans to birds or other animals, the many similarities in physiology between humans and birds, and the reliance of both on sound for communication, suggests the possibility that stress and physiological effects on humans may be paralleled in birds (and other terrestrial vertebrates).

B. Birds and Traffic and Construction Noise

As pointed out at the beginning of this Guidance Document, the world is becoming a noisier place and the cost of chronic noise exposure for terrestrial organisms could become significant (Barber *et al.*, 2010; Pijanowski *et al.*, 2011a., b; Luther and Magnotti, 2014; Merchant *et al.*, 2015). When the original 2007 report (Dooling and Popper, 2007) was written, there were relative few well-controlled studies on the effects of traffic noise on birds and a considerable amount of grey literature consisting of uncontrolled studies and anecdotal observations studies all suggesting the possibility of negative effects of traffic noise on birds. For instance, at that time there were reports from several investigators, later confirmed and published, suggesting that there may be differences in vocalizations between city birds and country birds, with city birds generally singing at a higher

pitch presumably due to greater amounts of low frequency noise from urbanization, including traffic noise (Nemeth and Brumm, 2009; Nemeth and Brumm, 2010a; Slabbekoorn *et al.*, 2012). However, these studies in aggregate also led to two other inescapable conclusions: there were likely to be large species differences in susceptibility to increased noise, and there is an enormous challenge ahead in pinpointing the precise effects of traffic and construction noise on birds.

However, in the past eight years, there has been a number of more refined laboratory and experimental field research and observations published in peer-reviewed journals that has clarified some of the outstanding issues that were identified in earlier work. There is now a body of scientific literature which allows much stronger statements regarding the effects of noise on birds and the strategies birds use to adapt to increasing noise levels. While there are still numerous questions, especially with regard to species differences, it is overwhelmingly clear that many species of birds do respond to traffic noise (though no studies have focused on construction noise). However, it is also becoming apparent, as also discussed below, that many bird species successfully use the same kinds of strategies that humans and other animals use to hear and communicate in a noisy environment such as that created by traffic noise.

Results up to 2007: Many of the key issues involving the effects of traffic noise on birds were raised in the earlier literature, as were suggestions for future research. More recent findings have relied on this earlier work, and there is now a growing body of data that resolve some of the earlier issues. This Guidance Document focuses a review on this more recent data. For a complete review of the earlier work, please refer to the original report (attached as Appendix

Many of these earlier studies were in a very real sense pioneering. They also in many cases revealed considerable species variation and often did not have sufficient control of critical variables; therefore, these studies could not isolate the potential effects of highway noise on birds or provide general guidance (Clark and Karr, 1979; Ferris, 1979; Van der Zande *et al.*, 1980; Reijnen and Foppen, 1994; 1995; Reijnen *et al.*, 1995; Lee and Fleming, 1996; Llacuna *et al.*, 1996; Kuitunen *et al.*, 1998; Reijnen *et al.*, 1998; Clench-Aas *et al.*, 2000; Stone, 2000; Fernández-juricic, 2001; Forman *et al.*, 2002; Peris and Pescador, 2004). This literature has been reviewed several times in recent years (e.g., Sarigul-Klijn *et al.*, 1997; Kaseloo, 2005; Warren *et al.*, 2006; van der Ree *et al.*, 2011; Ortega, 2012; Slabbekoorn *et al.*, 2012; Merchant *et al.*, 2015); therefore, it will not be re-reviewed here. Instead, issues arising from this earlier work are listed below as a framework in which to understand the more recent, and generally more scientifically rigorous, work that has followed.

1) What evidence is there to suggest that results from one species or set of conditions can be generalized to all bird species?
2) Which aspects of a bird's behavior are likely to be affected by traffic noise?
3) How can one be sure that the effects of traffic noise on a bird is due to noise and not to other accompanying visual (i.e., moving vehicles) or olfactory (i.e., exhaust emissions, or tactile (i.e., vibration) stimuli?
4) Most studies are of adult birds. What are the effects of traffic noise on birds that must learn their vocalizations from auditory information?
5) Laboratory masking studies typically use white noise. Do the general masking principles emerging likely to hold for other anthropogenic noises?

Studies Since 2007: Many of the more recent studies discussed below add more high-quality information to the growing body of literature on this topic. Other studies are aimed specifically at some of the lingering questions from the last review and now allow conclusions on these questions, leading to an overall better understanding of how construction and traffic noise could impact birds.

Regarding the prevalence of noise effects on birds, a within-genera comparison of singing in 529 bird species within 109 genera has recently showed that species occurring in urban environments generally vocalize at higher frequencies than non-urban congeneric species without differing in body size or the vegetation density of their natural habitats (Hu and Cardoso, 2009, 2010). For example, white-crowned sparrow (*Zonotrichia leucophrys*) song increased in minimum frequency from 1969 to 2005 in San Francisco, and male birds responded more strongly to current songs than to earlier songs indicating current songs are most effective in the noisier environment (Luther and Baptista, 2010a; Luther and Derryberry, 2012; Luther and Magnotti, 2014).

For some species, it is clear that the whole communication process is affected and not just by the level of noise but by the actual signal-to-noise ratio. European robins (*Erithacus rubecula*) were presented with two playback songs, one with noise, one without; the male birds responded to the song in noise with increased minimum frequency and decreased song complexity and song duration (McMullen *et al.*, 2014).

In another study, low frequency traffic noise reduced female canary responsiveness to low-frequency, more attractive songs but did not affect responsiveness to high-frequency songs (Huet des Aunay *et al.*, 2014). In the great tit (*Parus major*), low frequency songs by males are related to female fertility and sexual fidelity. Urban noise impairs male-female communications shifting communication to higher frequency songs (Halfwerk *et al.*, 2011). Interestingly, artificial noise in nest boxes shows that female great tits can steer male singing behavior under noisy conditions, making males sing closer to the nest boxes even though males were not themselves exposed to noise (Halfwerk *et al.*, 2012). In another study, great tits were 6 dB better at detecting high frequency songs than low frequency songs in urban noise, but not in woodland noise. Moreover, discrimination between low frequency variants of song was less efficient than discriminating high frequency variants. High frequency elements were used by birds in urban noise, while all song elements were used in discriminating between songs in woodland noise (Pohl *et al.*, 2012).

A great deal of research has also examined the relation between the increase in vocal intensity and the increase in vocalization frequency and whether there is a cause-effect relationship between these changes or if they occur independently (reviewed in (Zollinger *et al.*, 2012). Some birds adjust both loudness and peak frequency in their songs to compensate for traffic noise rather than simply adjusting loudness with a correlated frequency shift (Cardoso and Atwell, 2011). Other species vary multiple parameters. With increasing noise levels, plumbeous vireos (*Vireo plumbeus*) sang shorter songs with higher minimum frequencies while grey vireos (*Vireo vicinior*) sang longer songs with higher maximum frequencies suggesting that vocal plasticity may help some species occupy noisy areas (Francis *et al.*, 2011a, b). But the results are likely environmentally determined. The common blackbird (*Turdus merula*) preferentially sang higher frequency songs elements that can be produced at higher intensities and, at the same time, are less masked by low frequency traffic noise (Nemeth *et al.*, 2013b).

But it was also shown that for the common blackbird and the great tit, increasing frequency (song pitch) was less effective at increasing communication distance in noisy environments than was increasing vocal amplitude (Nemeth and Brumm, 2010a). Silvereyes (*Zosterops lateralis*) exposed to low and high frequency noise lowered the minimum frequency of their calls, and this shift was independent of amplitude which increased in all noises. Thus, silvereyes are clearly capable of flexible adjustments of call frequency, amplitude, and duration to maximize signal-to-noise ratio in noisy environments (Potvin and Mulder, 2013).

The variation noted in the earlier literature is still a leading finding. There are substantial species differences in which song features are adjusted. In the house wren (*Troglodytes aedon*), anthropogenic noise reduced bandwidth, increased trill rate, and increased minimum frequency (Redondo *et al.*, 2013). On the other hand, both northern cardinals (*Cardinalis cardinalis*) and American robins (*Turdus migratorius*) increased frequency range as noise increased but did not change song length or singing rate (Seger-Fullam *et al.*, 2011). A study in house sparrows (*Passer domesticus*) revealed that chronic noise exposure reduced fitness by masking parent-offspring communication rather than male-female communication (Schroeder *et al.*, 2012). Moreover, black-capped chickadees (*Poecile atricapillus*) use shorter, higher frequency vocalizations when traffic noise is high, and longer, lower frequency songs when noise abates (Proppe *et al.*, 2011). The same species sing at higher pitches with elevated anthropogenic noise but not with decreasing canopy cover, suggesting noise is the main factor, and not vegetation, that leads to increased song pitch (Proppe *et al.*, 2012). Finally, a pattern seen among seven songbird species is that noise contributes to declines in urban diversity by reducing the abundance of select species in noisy areas, especially species with low frequency songs (Proppe *et al.*, 2013).

Noise effects are complex, usually related to level, and can be both short- and long term. Serins (*Serinus serinus*), a small European songbird related to canaries, responded to increasing levels of anthropogenic noise by increasing song activity up to noise levels of about 70 dBA, after which singing activity decreased with further increases in noise level (Díaz *et al.*, 2011). Male cardinals gave stronger responses to songs of average frequency than to songs with shifted frequency at low levels of background noise, but the difference disappeared at high noise levels, suggesting that frequency shifted songs were not advantageous in terms of communication at higher noise levels (Luther and Magnotti, 2014). Red-winged blackbirds (*Agelaius phoeniceus*) increased song tonality when temporarily exposed to low frequency white noise, and birds living in noisier environments showed increased tonality when singing in quiet, suggesting both short-term and long-term effects (Hanna *et al.*, 2011). On the other hand, male red buntings (*Emberiza bruniceps*) adjusted their songs immediately in response to noise singing at higher frequency and a lower rate when noise level were high, suggesting short-term, rather than long-term, adaptations (Kane *et al.*, 2010).

The effects of noise on bird songs are usually, but not always, negative. The female American kestrel (*Falco sparverius*) had higher cortisol levels and abandoned nests more frequently near busy roads and developed areas (Strasser and Heath, 2013). In a study of a number of bird species in northwestern New Mexico, noise alone decreased nesting species richness and this led to different communities of birds with less interaction with one another. But, unexpectedly, this same noise indirectly facilitated reproductive success of individuals nesting in noisy areas as a result of disruption of predator–prey relationships (Francis *et al.*, 2009). Experimental noise exposure data in six European songbird species revealed a noise-related earlier start of dawn singing for two out

of six species but revealed no impact on four species with more variable starting times for dawn singing (Arroyo-Solís *et al.*, 2013).

Another study of six different American songbird species also found that the effects of urban noise on song were mixed. Minimum song frequency increased with noise level for two species, with those species singing in lower frequencies being most affected. On the other hand, maximum frequency and frequency range decreased for two species, with increasing urban noise at quiet sites (Dowling *et al.*, 2011). A recent paper examined the effects of noise on a bird's ability to discriminate between various levels of song degradation—a cue used by birds to gauge the distance from other singing birds. The great tit's overall responses in a noisy dawn chorus were, unexpectedly, very similar to their performance in silence.

Finally, Ware et al. (2015) conducted a well-controlled and designed study that separated the effects of traffic noise from the other sensory effects that accompany traffic noise such as exhaust (i.e., olfactory) and vehicular traffic (i.e., visual) by creating a "phantom road." Results across species were decidedly mixed. Some species avoided the noisy area, and some lost weight, while others did not. It's possible that presenting traffic noise without the attendant visual (e.g., moving vehicles), olfactory (i.e., exhaust emissions), and tactile (i.e., vibration) cues is itself stressful to some birds because these cues all normally occur together. Results from these recent studies confirm that the effects of traffic noise remain complicated and are highly likely to vary by species and other conditions (see also Merchant *et al.*, 2015).

Recent studies with young birds and nestlings, add even more complexity to the mixed effects described above. Young birds would not be expected to have had experience with noisy objects, such as vehicles, in their environment and, thus, the effects of noise alone might be easier to gauge. Crino et al (2013) showed nestling white crowned sparrows (*Zonotrichia leucophrys*) exposed to traffic noise had lower glucocorticoid levels and improved condition relative to control nests. Nestling Eastern bluebirds, young enough to be constrained to the nestling box were recorded in their natural habitat at various locations from quiet to near highways, parking lots, and other noisy environments. Birds did not increase the amplitude or structural characteristics of the begging calls in response to increasing noise levels (Swaddle *et al.*, 2012). On the other hand, a recent study on zebra finches by Potvin and MacCougall-Shackleton (2015) showed that chronic, long-term exposure to traffic noise in an experimental setting had both immediate and long-term effects on song but not in a way that would reduce masking. Moreover, the noise exposure resulted in a decrease in corticosterone suggesting reduced stress.

Finally, a recent study examined the effects of traffic noise played to juvenile free-living house sparrows (*Passer domesticus*) and showed that exposed birds had shorter telomeres (chromosome ends) than birds not exposed, although the experimental and control birds were identical in all other ways, including health (Meillère *et al.*, 2015). Telomeres decrease in size with aging, and it is generally accepted that there is a correlation between telomere length and longevity. Thus, these results, though the first of their kind and only for single species, suggest a new mechanism by which traffic noise might affect birds.

The emerging picture from the latest research on the effects of noise on birds is one of more careful data collection and focused research designs but with complex outcomes still occurring and large species differences still the rule. Finally, extreme noise events may also have more extreme effects.

Using weather radar technology, it was documented that thousands of birds take flight following evening fireworks displays lasting 45 min. The peak densities of fleeing birds extended to altitudes of at least 500 feet (Shamoun-Baranes *et al.*, 2011). While this is the only report of its kind, it may have implications for the effects of short-term, high-level construction noise, especially when it occurs at night.

Summary of Recent Studies on Effects of Traffic Noise on Birds: The overall picture that emerges from the research since 2007 is still one of considerable complexity and variation. It is now abundantly clear that noise has a widespread effect on many species of birds. However, this is not to say that it is any easier to predict the specific effects of traffic noise on any particular species in its natural habitat. The recent literature also shows that the same noise can affect different species sometimes in the same way but often in different ways. And it is still the case that there are clear examples where traffic noise actually benefits a species rather than causing harm.

Nevertheless, it is difficult to argue with the notions that the world is an increasingly noisy place and noise affects birds and interferes with their acoustic communication. It follows that there should be an effort made to monitor anthropogenic noise and decrease noise levels where possible. The challenge in pinpointing specific effects of noise or finding invariant noise levels that cause harm across conditions should not be surprising. The same lack of specificity is true of humans living and communicating in noisy environments. Personal experiences (e.g., conversing in a noisy restaurant) make it clear that humans can and do employ a plethora of both short-term and long-term adaptive strategies for communicating effectively in noise, which makes it impossible to determine that a particular type or level of noise is accurately predictive. It is evermore clear from field studies and well-controlled laboratory studies that birds can and do use human-like strategies, described below, for counteracting the effects of an increasingly noisy environment. And, as with humans, it is possible from laboratory studies on birds to define a level of noise that would represent a "worst case" scenario in terms of interfering with acoustic communication. In other words, there is a precise signal-to-noise ratio at the ears below which communication is impossible without employing short term adaptation strategies (i.e., those typically available to freely moving birds in their natural habitat). That signal-to-noise value comes from laboratory studies and is the critical ratio.

C. Short-Term Adaptations to Noise Masking

A critical question is how birds, or any animal, including humans, adapt to noise (traffic) masking in the short term. Based on both highly controlled laboratory and field studies, it is apparent that in natural settings, birds can use many strategies to maximize their hearing in noise. For one, birds are able to adjust the characteristics of their vocalizations in response to temporary changes in the background noise. There is now a considerable amount of literature demonstrating that birds can adjust the amplitude of their vocalizations in response to increased noise by a phenomenon first referred to in humans as the Lombard effect. A number of species of birds have been shown to raise the level of their vocal output by as much as 10 dB in the presence of moderate background noise that is loud enough affect the bird's perception of its own vocalizations (Potash, 1972; Cynx *et al.*, 1998; Manabe *et al.*, 1998; Brumm and Todt, 2002; 2003; Hu and Cardoso, 2010; Nemeth *et al.*, 2013a).

The ability of birds to adjust vocalization in the presence of noise has now been demonstrated by studying behaving birds trained to wear headphones while vocalizing (Osmanski and Dooling, 2006). In these experiments, presenting noise through headphones caused the bird to raise the amplitude of vocal output by as much as 10 dB. These highly controlled laboratory studies are now complemented by a variety of field studies such as a study showing that males of the common nightingale (*Luscinia megarhynchos*) sing louder in noisier territories, and birds in urban areas sing louder on working days than on weekend days when noise levels are reduced (Brumm, 2004).

Paralleling what is known from humans communicating in noise, there is limited evidence that at least some birds use repetition rate or increases in call duration to increase the efficiency of signal transmission. Japanese quail increase the number of call syllables per call series in noise (Potash, 1972) and king penguins (*Aptenodytes patagonicus*) respond to increasing levels of background noise due to wind by increasing the number of syllables in their calls (Lengagne *et al.*, 1999).

Birds are also capable of making short term alterations in the spectrum of their vocalizations (Hultsch and Todt, 1996; Manabe, 1997). The basic mechanisms for this was more recently examined in budgerigars trained to produce vocalizations while wearing headphones. Such birds can be induced to pitch-shift their vocalizations in real time. Artificially shifting the pitch of auditory feedback of the bird's own vocalizations resulted in the bird compensating by shifting the pitch of its vocalization in the opposite direction (Osmanski and Dooling, 2009). These experiments demonstrate that birds have some short-term control over the pitch of their vocalizations and may use this ability to maximize information transfer in a noisy environment.

Clearly, humans can choose to communicate when noise levels are low and limit communication when noise levels are so high as to make communication impossible. It is also well known that birds can adjust the timing of their vocalizations to avoid competition for acoustic space with other species or to coincide with low noise periods to prevent auditory masking (Cody and Brown, 1969; Wasserman, 1977; Ficken *et al.*, 1985; Popp *et al.*, 1985; Popp and Ficken, 1987; Evans, 1991; Luther and Baptista, 2010b; Nemeth and Brumm, 2010b).

Birds (both senders and receivers) can also behaviorally counteract the effects of masking noise on acoustic communication by changing their location. One strategy that can improve signal-to-noise ratio is to move to a position in the habitat in which the transmission pathway is better for the signal than the noise (Brumm and Slabbekoorn, 2005). Thus, moving higher up into the canopy of the vegetation is another response that will improve the signal-to-noise ratio (Mathevon *et al.*, 1996; Holland *et al.*, 1998). With European blackbirds *(Turdus merula)*, it is estimated that moving up from the ground to a perch at about 9 meters (29.5 feet) high would result in an increase in audibility that is comparable to the receiver moving 90 meters (295 feet) closer to the sender horizontally (Dabelsteen *et al.*, 1993).

Birds (like humans and other binaural animals) enjoy a "spatial release" from masking when the noise source is spatially separated from the signal source. That is, when the signal to be detected comes from a different location in space than the noise, having two ears leads to an improvement in signal detection (Popper and Fay, 2005). In human hearing, this can represent a large effect, but there were some questions whether birds, with their closely spaced ears, would enjoy a similar benefit (Dent *et al.*, 1997). A Laboratory study with budgerigars under controlled conditions has

shown that the amount of this masking release is can be as much as 10–15 dB when the noise and the signal arrive at the bird's ears from 90 degrees apart (Dent *et al.*, 1997) paralleling the advantage gained by humans when they scan the environment using head movements to hear a weak acoustic signal. Recalling that sound pressure decreases roughly 6 dB with each doubling of distance, this could translate into a quadrupling of distance over which two birds could communicate if they position themselves optimally with regards the noise source (i.e., at 90 degrees).

D. Long-Term Adaptations to Noise Masking

Even without human-generated noise, natural habitats have particular patterns of ambient noise (the acoustic scene) resulting from, among other things, wind, animal and insect sounds, and other noise-producing environmental factors such as a streams, waterfalls, etc. Biologists have long suspected that such noise has exerted a selection pressure on the evolution of acoustic signals, especially in birds (e.g., Morton, 1975; Brenowitz, 1982; Wiley and Richards, 1982; Ryan and Brenowitz, 1985; Slabbekoorn, 2004; Smith *et al.*, 2008, 2013). Brumm and Slabbekoorn (2005) reported that the large-billed leaf-warbler (*Phylloscopus magnirostris*), which lives close to river torrents in the Himalayas, evade masking of their territorial songs by producing high-pitched notes in narrow frequency bands around 6 kHz (Dubois and Martens, 1984). In fact, differences in song or call structure based on differences in habitat have been reported, or suspected, in a number of avian species (Douglas and Conner, 1999; Slabbekoorn and Smith, 2002; Slabbekoorn and Peet, 2003), such as for the songs of little greenbuls *(Andropadus virens).* It remains an intense area of study as to whether a given vocalization is adapted to environmental noise by evolutionary or ontogenetic changes or both.

E. Estimating Maximum Communication Distance between Two Birds Using Laboratory Masking Data

The question of whether noise affects vocalization structure raises a parallel question of how much noise is too much. In other words, how loud does a noise have to be before the bird must begin to alter the structure of its vocalizations in order to communicate? To address this question with quantitative rigor, Lohr *et al*. (2003) examined the effects of masking on the detection and discrimination of species-specific vocalizations in zebra finch and the budgerigar using two different types of continuous noise—one a flat, broadband noise and the other shaped like traffic noise with more energy at low frequencies and less at high frequencies**.**

Lohr and his colleagues used both budgerigar vocalizations (narrow band and tonal) and zebra finch vocalizations (broadband and harmonic) and measured both detection and discrimination because being able to detect a sound is not the same as being able to discriminate effectively between sounds or to recognize a particular sound. Results show exactly this for —it requires slightly better signal-to-noise ratio for birds to discriminate between two sounds in noise than to detect the sounds in noise at equivalent levels of performance. This is much like the case of perceiving speech in human listeners where hearing or detecting speech is not the same as actually hearing it well enough to understand what is being said.

These results enabled the investigators to estimate the theoretical maximum communication

distance (d_{mc}) by solving the following equation adopted from Marten and Marler (Marten and Marler, 1977) and Dooling (Dooling, 1982):

$$\text{Drop} = 20 \cdot \log\left(\frac{d_{mc}}{d_o} + \frac{EA \cdot d_{mc}}{100}\right)$$

Drop: the amount of signal attenuation from source intensity to that at threshold;
d_{mc}: the maximum communication distance;
d_o: the distance at which source intensity is measured; and
EA: the amount of excess attenuation (linear attenuation, not due to spherical spreading).

Solving the above equation for both detection and discrimination of each species calls in both types of noise, and it is possible to generate a series of curves to describe maximum effective communication distances for a given level of background noise (Lohr *et al.*, 2003). In this analysis, a source intensity level of 95 dB SPL at 1 meter was assumed, as was an excess attenuation of 5 dB/100 meters (appropriate for an open area) (Lohr *et al.*, 2003). These values fall within the range of those measured in the field but are near the high end for source intensity (Brackenbury, 1979a, b) and the low end for excess attenuation (Marten and Marler, 1977; Brenowitz, 1982).

Such an approach provides a way to estimate maximum communication distance under fairly good conditions from the perspective of a receiver and revealed both species differences and vocalization differences. The results demonstrate that it is easier for birds to hear vocalizations in traffic noise than flat noise. A bird can detect and discriminate budgerigar calls at longer distances than it can zebra finch calls. Budgerigars do better than zebra finches. And the distances over which signals may be discriminated are shorter than distances at which those same signals may be detected. These predictive distances from the laboratory masking data do not take into account any gains from short term adaptation strategies animals are able to use in their natural habitats. So, the distances obtained from this model represent the worst case scenario.

F. Putting It All Together—Predicting the Effects of Noise on Bird Acoustic Communication

It is clear that acoustic communication can be constrained if background noise is of a sufficient level, and can become impossible in very high noise levels. These effects occur because the noise decreases signal-to-noise ratios, thereby limiting the acoustic space of a sound. Noises can be continuous or intermittent, broadband or narrowband, and predictable or unpredictable in time or space. Background noise makes it harder for an animal (including humans) to detect sounds that may be biologically relevant, to discriminate among these sounds, to recognize these sounds, and to communicate easily.

Since the early studies by Lohr *et al*. (2003), more recent work (Dooling and Blumenrath, 2014) has elaborated on predicting communication distance in noise by considering not just detection and discrimination, but other meanings of hearing, including recognition and comfortable communication. It is now clear that signal discrimination requires a higher signal-to-noise ratio

than detection; that recognition in both humans and birds requires an even higher signal-to-noise ratio than discrimination; and comfortable communication requires an even higher signal-to-noise ratio (Lohr *et al.*, 2003; Freyaldenhoven *et al.*, 2006). Interestingly, there is about a 3 dB difference in signal to noise ratio required between detection (i.e., the critical ratio) and discrimination, and between discrimination and recognition for both birds and humans. It is not possible to measure comfortable communication in a bird, but in humans a signal-to-noise ratio of about 15 dB is required. The similarity between birds and humans on the different signal-to-noise ratios required for detection, discrimination, and recognition strongly suggest that the 15 dB signal-to-noise ratio required for comfortable communication can probably also be applied to birds.

The approach developed from the above discussion integrates the spectrum level of the masking noise, how well the bird hears in noise (i.e., the critical ratio), the level at which the bird sings (Brackenbury, 1979b), as well as some simple acoustic characteristics of the environment. The model is based on the spectrum and the level of both the noise and the signaler's vocalization at the receiver's ear. These values for spectrum and level of noise and signal can either be measured directly or they can be estimated by applying signal attenuation algorithms to both the noise source and the signal source. The model is particularly relevant because it incorporates the notion that different auditory behaviors from detection (i.e., the critical ratio) to communicating comfortably (i.e., 15 dB greater signal-to-noise ratio than the detection threshold). For the listening bird, the model provides distances corresponding to the human perceptual experience of communicating comfortably versus just being able to detect that something was said.

Figure 9 shows the effects of anthropogenic traffic noise on four different auditory behaviors based on the median bird critical ratio function (see Figure 7 and discussion of masking). The specific case illustrated is for a background noise level at the listening bird of 60 dBA—a level that is typical of traffic noise measured roughly 300 meters (984 feet) from a busy 6 lane roadway. This example assumes the calling bird is vocalizing at a peak SPL of 100 dB (as measured 1 meter (3.3 feet) from the bird) through an open area and that the vocalization is affected by excess attenuation, in addition to the loss due to spherical spreading, of 5 dB/100 meters (328 feet).

In this noise, a comfortable level of communication between two birds requires a distance between them of less than 60 meters (197 feet). Recognition of a bird vocalization by the receiver can still occur at greater inter-bird distances up to about 220 meters (722 feet). Discrimination between two vocalizations is possible at inter-bird distances up to 270 meters (886 feet). And finally, simple detection of another bird's vocalization can occur at distances up to 345 meters (1,132 feet) in this noise. These findings can be plotted in terms of a bird's active auditory space as in shown in Figure 10 as a set of concentric circles with a listening bird in the center and a calling bird located at various distances from the listener representing the kind of auditory behavior that is possible at that distance.

G. Defining Guidelines for Effects

The model described above (Lohr *et al.*, 2003; Dooling *et al.*, 2009; Dooling and Blumenrath, 2014) incorporates many factors that should be considered when establishing guidelines for the effects of traffic and construction noise on birds. Based on psychophysical thresholds measured in a laboratory setting, it shows maximum communication distance for a typical bird in a natural setting based on the intensity with which the bird vocalizes and the transmission loss from the

environment due to the excess attenuation. The threshold for effect would also have to take into account what is known about the spectral characteristics of vocalizations, the distance over which conspecific acoustic communication (e.g., the territory size) normally occurs, and the existing levels of ambient noise. Noise levels that limit the maximum communication distances to a distance that is less than the diameter of the bird's territory size (or known communication distances in ambient noise) may have serious biological consequences. The level of natural ambient noise already present in the bird's environment is a key factor in determining whether additional noise from traffic and construction would have any effect. Traffic or construction noise below ambient noise levels would not affect communication.

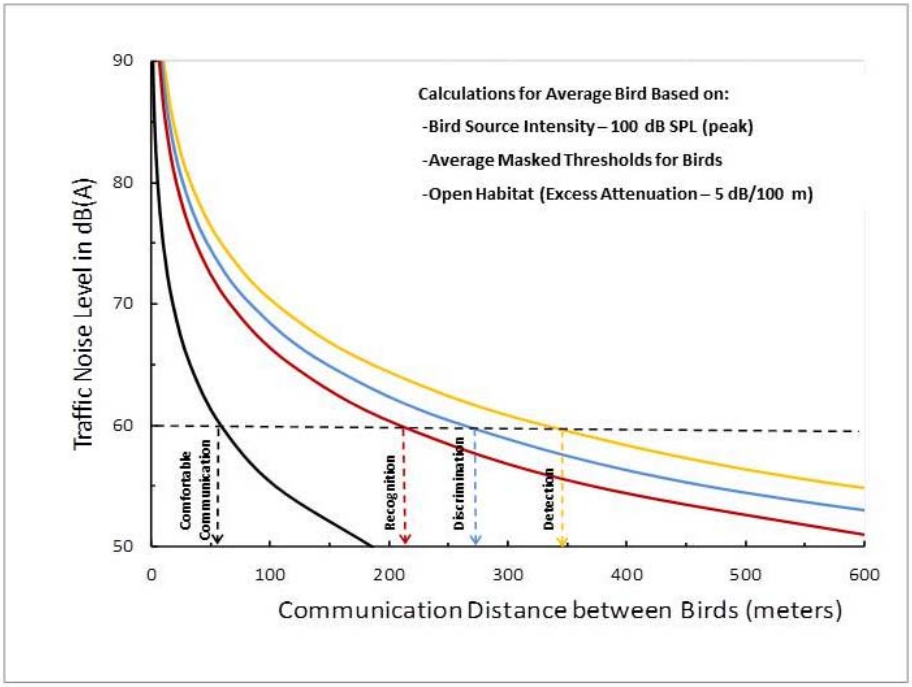

Figure 9: The Effects of Anthropogenic Traffic Noise on Four Different Behaviors Based on the Average Bird Critical Ratio Function

Based on the traffic noise spectrum shown in Figure 2 at a level of 60 dBA, comfortable communication occurs up to 60 meters; recognition of a vocalization can occur up to about 110 meters; discrimination between two vocalizations at about 270 meters, and detection at about 340 meters. Beyond this distance, a bird is not likely to detect the signal. This is based on laboratory critical ratio data and, thus, defines a worst case scenario. In a natural setting, birds would be expected to use their demonstrated short-term adaptation strategies for communicating in noise.

Clearly, variation in territory size, the size of the critical ratio among birds, and natural ambient noise levels are key variables that make it impossible to use a single noise level as a one-level-fits-all level in terms of estimating whether traffic and/or construction noise is limiting communication distance by causing additional masking. In fact, species differences and habitat differences can make rather large differences in the distance. There are species differences in critical ratios and therefore these plots would look different for different species. Because budgerigars hear better in noise (smaller critical ratios) than, for instance, canaries, under the same conditions of an open habitat canaries would a much smaller active vocal space than do budgerigars in the same amount of noise. The model used here is successful in predicting communication distance in a variety of

environments and a variety of species. When this model is combined with commercial software (e.g., SoundPlan[20]) for predicting noise characteristics at different distances from a highway, a map can be made describing the bird's communication difficulty at any location from the highway.

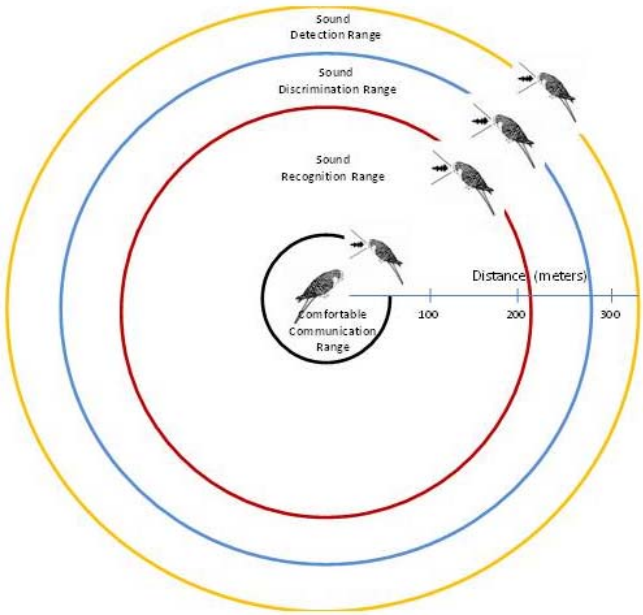

Figure 10: Diagrammatic Representation of Bird Communication

A diagrammatic representation of data in Figure 9 showing the quality of hearing for a bird in noise located at different distances from a sound-emitting bird. A bird can just hear a vocalizations (i.e., detect it) at a much greater distance than is required for comfortable communication. This represents the worst case scenario based on critical ratio data from the laboratory and does not include short-term adaptation strategies described earlier, which would improve communication.

Based on laboratory data, this Guidance Document recommends several guidelines—two dealing with hearing damage and threshold shift, one dealing with masking, and a fourth dealing with stress and annoyance. As illustrated in Figure 3, these guidelines are as follows.

(1) Received noise levels less than 110 dBA SPL continuous are extremely unlikely to cause hearing damage or permanent threshold shift in birds.
(2) Received continuous noise levels below 93 dBA SPL are unlikely to cause even temporary threshold shifts in birds. This value, based solely on bird studies, is in harmony with much of the literature on human hearing. Consider, for example, that OSHA standards require hearing conservation procedures only when noise levels in the workplace reach continuous levels of 85 dBA for 8 hours.
(3) At further distances from the highway, once the received level of traffic and construction noise falls below the ambient noise level (particularly in the region of 2-4 kHz), there is little or no additional masking of communication signals beyond what already occurs from natural ambient noise.
(4) In the absence of empirical data from birds, received levels of traffic and construction noise known to annoy humans provide a useful interim guideline for the potential to cause

[20] http://www.soundplan.eu/english/soundplan-acoustics/

physiological stress and behavioral disturbance in birds. Generally, construction noise, because it is both short term and more intermittent, is likely to have less of an effect that traffic noise. This is expected except in rare in cases where birds may remain in close proximity to very high level impulsive noise as from pile driving.

Two common sense guidelines also arise from review of the data on masking. First, the typical human listener can hear traffic and construction noise at distances 2–4 times greater than can the typical bird. It follows that traffic and construction noise from either traffic or construction activity that is just barely audible to humans at any given distance, almost certainly cannot be heard by birds at the same distance. Second, the converse is also true, if a human listener can barely hear a bird singing against a background of traffic and construction noise, masking data suggest that another bird would have to half again as close to singing bird in order to hear it. In this case, using human hearing as a guide underestimates the effects of noise on bird communication.

5. Summary and Overview of the Effects of Traffic Noise on Birds

1) Stress and physiological effects:
   a) There are no studies definitively identifying traffic noise as the critical variable affect bird behavior near roadways and highways.
   b) There are well-documented adverse effects of sustained traffic noise on humans, including stress, physiological and sleep disturbances, and changes in feelings of well-being that may be applicable, when viewed with care, to birds.
   c) Traffic/construction noise below the bird's masked threshold has no effect.

2) Acoustic over-exposure:
   a) Birds are more resistant to both temporary and permanent hearing loss or to hearing damage from acoustic overexposure than are humans and other animals that have been tested.
   b) Birds can regenerate the sensory hair cells of the inner ear, thereby providing a mechanism for recovering from intense acoustic over-exposure, a capability not found in mammals.
   c) The studies of acoustic over-exposure in birds have considerable relevance for estimating hearing damage effects of traffic noise, non-continuous construction noise, and for impulsive-type construction noise such as pile drivers.

3) Masking:
   a) Continuous noise of sufficient intensity in the frequency region of bird hearing can have a detrimental effect on the detection and discrimination of vocal signals by birds.
   b) Noise in the spectral region of the vocalizations has a greater masking affect than noises outside this range. Thus, traffic noise will cause less masking than other environmental noises of equal overall level but that contain energy in a higher spectral region around 2–4 kHz (e.g., insects, vocalizations of other birds).
   c) Generally, human auditory thresholds in quiet and in noise are better than that of the typical bird, which leads to the following conclusions:
      (1) The typical human will be able to hear single vehicle, traffic noise, and construction noise at a much greater distance from the roadway than will the typical bird, thereby providing a valuable, common sense, easy-to-apply, risk criterion.

(2) However, the typical human will also be able to hear a bird vocalizing in a noisy environment at twice the distance that a typical bird, meaning that relying on human hearing underestimates the effects of noise on bird communication.

d) From knowledge of: (i) bird hearing in quiet and noise, (ii) the Inverse Square Law, (iii) Excess Attenuation in a particular environment, and (iv) species-specific acoustic characteristics of vocalizations, reasonable predictions can be made about possible maximum communication distances between two birds in continuous noise.

e) The amount of masking of vocalizations can be predicted from the peak in the total power spectrum of the vocalization and the bird's critical ratio (i.e., signal-to-noise ratio) at that frequency of peak energy.

f) Birds, like humans and other animals, employ a range of short-term behavioral strategies, or adaptations, for communicating in noise, resulting in a doubling to quadrupling of the efficiency of hearing in noise.

4) Dynamic behavioral and population effects:

a) Any components of traffic noise that are audible to birds may have effects independent of and beyond the effects listed above. At distances from the roadway where traffic noise levels fall below ambient noise levels in the spectral region for vocal communication (i.e., 2–8 kHz), low level but audible sound in non-communication frequencies (e.g., the rumbling of a truck) can potentially cause may cause physiological or behavioral responses). Beyond effects due specifically to traffic noise, since the more recent literature points to noise as possibly having wide ranging effects on birds, consideration must be given to the additive effects of traffic noise and environmental noise.

5) Extrapolation of data from humans and birds to other species:

a) Since there is substantial variation in bird hearing and behavior, considerable care must be taken when trying to extrapolate data between species, and particularly when the species have different hearing capabilities and acoustic behaviors.

b) Data from humans has relevance to understanding effects of sound in birds. In particular, data on physiological effects in humans may have implications for birds, but additional study is needed.

6) Much more data are needed on:

a) Physiological effects of sound on birds.

b) How responses vary between species with regard to masking, hearing loss, and hearing recovery.

c) Hearing in young animals and how this compares to that in adults.

d) Additional, and carefully selected, species so there is a large enough database from which to allow extrapolation between species, and broader generalizations on effects of noise on birds.

e) A broader range of studies, as discussed in detail in Appendix F.

6. Estimating Effects of Traffic Noise on Birds, Rationale, and *Interim* Guidelines

This Guidance Document has reviewed three classes of potential effects of traffic noise on birds. The basis of the guidelines for each class of effects differs. Table 3 and Figure 3 provide specific *interim* criteria.

1. *Behavioral and/or physiological effects*: There are no definitive studies showing that traffic noise exclusively (as opposed to correlated variables) has an adverse effect on birds. While a wealth of human data and experience suggest traffic noise could have a number of adverse effects, there are several studies (e.g., Awbrey *et al.*, 1995) showing that birds (as well as other animals) adapt quite well, and even appear sometimes to prefer, environments that include high levels of traffic noise. Given the lack of empirical data on this point, it is recommended using subjective human experience with the noise in question as an *interim* guideline to estimate acceptable noise levels for avoiding stress and physiological effects. Noise types and levels that appear to increase stress and adverse physiological reactions in humans may also have similar consequences in birds.

2. *Damage to hearing from acoustic overexposure*: In contrast to the above, there are many definitive studies showing the effects of intense noise on bird hearing and auditory structures. These extensive data show that birds are much more resistant to hearing loss and auditory damage from acoustic overexposure than are humans and other mammals. Traffic and construction noise, even at extreme levels, is unlikely to cause threshold shift, hearing loss, auditory damage, or damage to other organ systems in birds and, therefore, *interim* guidelines for hearing damage from traffic and construction noise are probably not needed. Construction noise, such as impulse noise from pile driving, does reach high levels and may be capable of causing damage to auditory structures in birds.

3. *Masking of communication signals and other biologically relevant sounds*: Many laboratory masking studies show precisely the effects of continuous noise (including traffic noise) on sound detection in over a dozen species of birds. These studies describe a sort of worst case scenario because the noise is continuous and the myriad of short-term adaptive behavioral responses for mitigating the effects of noise are not available to the bird in a laboratory test situation. These masking studies led to an overall noise level guideline of around 60 dBA for continuous noise. Since this 60 dBA criterion was developed, however, controlled laboratory and field studies have extended the range of species differences in signal-to-noise ratios as well as the gain in signal-to-noise ratio that occurs with various short-term, adaptive behavioral responses that birds might use in natural environments. Critical ratios vary across species as much as 10 dB, strongly suggesting that acoustic communication in some species might be affected by an overall traffic and construction noise level even less than 60 dBA, while others would not. For some other species, communication between individuals, especially if they can employ short-term behavioral strategies for hearing in noise, might be unaffected at even higher levels of noise perhaps approaching 70 dBA. These short term behavioral adaptations include scanning (head turning), raising vocal output, and changing singing location. Each of these strategies alone can result in a significant gain in signal level or signal-to-noise ratio of about 10 dB (under masking conditions), and birds can employ all three strategies simultaneously.

4. *Practical guidelines arising from masking studies*: There is a common sense, extremely practical guideline that emerges from basic hearing knowledge of birds and humans. Specifically, the 6 dB difference in masking (critical ratio) functions between the typical bird and human listeners with normal hearing provide two common sense guidelines: (1) Humans can hear traffic noise, in a natural environment, at twice the distance from the roadway/highway than can birds. In other words, if in a natural environment, distant traffic noise is barely audible to humans, it is certainly inaudible to birds, and will have no effect on any aspect of their acoustic behavior. (2) Humans can hear a bird singing against a background of noise at twice the distance than can the typical bird. This provides an informal estimate of maximum communication distance between two birds vocalizing against a background of continuous traffic noise. This works not only for the typical bird, but it is probably also valid for most species.

These recommended guidelines for estimating effects that traffic noise has on masking in birds are *interim* guidelines for several reasons.

1. The *interim* guidelines are based on median data from masking studies from a limited number of the thousands of bird species. Thus, they represent the typical bird, based on the species studied. However, it is important to recall that bird species can vary considerably in how they hear in the presence of noise; some have masked thresholds that approach those of humans, while others have masked thresholds that are 3–4 dB worse than thresholds for the typical bird presented here. Therefore, final noise guidelines will require testing more species with appropriate experimental adjustment for the species in question.

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2. Traffic noise characteristics are influenced by transmission through the environment, as are the spectral, temporal, and intensive aspects of bird vocalizations through differences in excess attenuation.

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Appendix A: Glossary

Altricial: Species that are in an undeveloped state at hatching or birth and require care and feeding from parents.

Audiogram: A measure of hearing sensitivity, or threshold, at each frequency in the hearing range of an animal or human.

Auditory brainstem response (ABR): A physiological method to determine hearing bandwidth and sensitivity of animals without training. Electrodes (wires) are placed on the head of the animal just outside of the base of the brain (brainstem) to record electrical signals (emitted by the brain) in response to sounds that are detected by the ear. These signals are averaged and used to determine if the animal has detected the sound. It is possible to determine auditory thresholds for fishes using this method. The same method is used for numerous other species, including measurement of hearing capabilities of newborn human babies.

Auditory threshold: The lowest detectable sound, generally at a specific frequency. Most often, thresholds are the level at which a signal is detected some per cent of the time—often 50% or 70%. Absolute thresholds are the lowest level of signal that is detectable when there is no background (masking) noise.

Bandwidth: The range of frequencies over which a sound is produced or received.

Basilar papilla: The auditory region of the inner ear of birds. The basilar papilla referred to as the avian cochlea since it may be evolutionarily related to the mammalian hearing organ, the cochlea.

Broadband: Defined as noise that covers a wide range of frequencies relative to which the ear is sensitive. In contrast, narrowband noise covers only a limited number of (contiguous) frequencies. In relation to bird or human hearing, for instance, a broadband noise might contain sound energy from 100 to 10,000 Hz, whereas a narrowband noise may contain sound energy from 500 to 550 Hz.

Critical ratio: Defined as the ratio of the intensity of a pure tone to the intensity per hertz of a noise (i.e., the spectrum level) at a listener's threshold. For example, if a listener can just hear a 60 dB pure tone against a background of noise whose spectrum level is 40 dB, the listener's critical ratio is said to be 20 dB. In fact, the human critical ratio at 2 kHz is approximately 20 dB.

Conspecific: A member of the same species.

Decibel (dB): A customary scale most commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the decibel value is defined to be 10 $\log_{10}$, (actual/reference), where (actual/reference) is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound

pressure is $20\log_{10}$ (actual pressure/reference pressure). As noted above, the standard reference for underwater sound pressure is 1 micro Pascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (i.e., re 1 µPa).

Effects: In this document, we have defined *effect* to mean any response by birds to traffic and construction noise. Our definition does not invoke or imply regulatory definitions of *effect*, as found in any law or regulation affecting birds.

Frequency spectrum: See *Spectrum*.

Hertz (Hz): The units of frequency where 1 hertz = 1 cycle per second.

Impulse sound: Transient sound produced by a rapid release of energy, usually electrical or chemical such as circuit breakers or explosives. Impulse sound has extremely short duration and extremely high peak sound pressure.

KiloHertz (kHz): A unit of frequency representing 1,000 Hz.

Noise: Generally an unwanted sound. Noise is often in the "ear of the beholder" in that a signal may be an important sound to one listener and unwanted "noise" to another.

Noise level: The noise power, usually relative to a reference level. Noise level is usually measured in decibels (dB) for relative power or picowatts for absolute power. Levels are represented in dB to denote specific aspects of the measurement and to also indicate the reference base or specific aspects of the measurement. Most frequently, sound levels for birds are referenced in terms of dB or weighted as dBA.

Octave: An octave is any band where the highest included frequency is exactly two times the lowest included frequency. For example, the frequency band that covers all frequencies between 707 Hz and 1,414 Hz is an octave band. The next octave band would be 1,414 to 2,828.

Ontogenetic: Development of an organism, usually from time of fertilization until it reaches its mature form.

Otolithic organs: The end organs in the vertebrate ear (saccule, utricle, lagena) associated with determination of head position relative to gravity. Along with the semicircular canals, these make up the vertebrate vestibular system.

Passeriformes: Song birds.

Permanent threshold shift (PTS): A permanent loss of hearing caused by some kind of acoustic or drug trauma. PTS results in irreversible damage to the sensory hair cells of the ear, and thus a permanent loss of hearing.

Power spectrum: "For a given signal, the power spectrum gives a plot of the portion of a signal's power (energy per unit time) falling within given frequency bins. The most common way of generating a power spectrum is by using a discrete Fourier transform, but other techniques such as the maximum entropy method can also be used."[21]

Semicircular canals: Three canals in the vertebrate ear that are mutually perpendicular to one another. They are involved in the detection of angular acceleration of the head, and provide the brain with information about movement of the head (and body). They are critically important to help maintain fixed gaze of the eyes on an object, even as the head moves. The semicircular canals and the otolithic organs make up the vestibular part of the ear.

Sensory hair cells: The cells in the basilar papilla and other end organs of the ear that are responsible for converting (transducing) mechanical energy of sound to signals that can stimulate the nerve from the ear to the brain (eighth cranial nerve).

Sound pressure level (SPL): The sound pressure level or SPL is an expression of the sound pressure using the decibel (dB) scale and the standard reference pressures 20 µPa for air and other gases.

Spectrum level: The intensity level of a sound within a 1 Hz band.

Spectrum (Spectra): A graphical display of the contribution of each frequency component contained in a sound.

Temporary threshold shift (TTS): Temporary loss of hearing as a result of exposure to sound over time. Exposure to high levels of sound over relatively short time periods will cause the same amount of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory hair cells. The duration of TTS varies depending on the nature of the stimulus, but there is generally recovery of full hearing over time.

Threshold: The threshold generally represents the lowest signal level an animal will detect in some statistically predetermined percent of presentations of a signal. Most often, the threshold is the level at which an animal will indicate detection 50% of the time. Auditory thresholds are the lowest sound levels detected by an animal at the 50% level.

Weighting: An electronic filter which has a frequency response corresponding approximately to that of human hearing. Human hearing is most sensitive to sounds from about 500 Hz to 4000 Hz, and less sensitive at lower and higher frequencies. The overall level of a sound is usually expressed in terms of dBA and this is generally measured using a sound level meter with an "A-weighting" filter. The level of a sound in dBA is a good measure of the loudness of that sound. Different sources having the same dBA level generally sound about equally loud.

[21] From: http://mathworld.wolfram.com/PowerSpectrum.html

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Appendix B: Complete Table of all Behavioral Studies of Hearing in Birds

Order	Common Name	Genus and Species	References
Anseriformes	mallard duck	*Anas platyrhynchos*	(Trainer, 1946)
Apodiformes	Australian grey swiftlet	*Collocalia Spodiopygia*	(Coles *et al.*, 1987)
Caprimulgiformes	oilbird	*Steatornis caripensis*	(Konishi and Knudsen, 1979)
Casuariiformes	emu	*Dromaius novaehollandiae*	(Manley *et al.*, 1997)
Charadriiformes	plains wanderer	*Pedionomus torquatus*	(Pettigrew *et al.*, 1990)
Columbiformes	pigeon	*Columbia livia*	(Trainer, 1946; Heise, 1953; Hienz *et al.*, 1977)
Falconiformes	American kestrel	*Falco sparverius*	(Trainer, 1946)
Falconiformes	European sparrowhawk	*Accipiter nisus*	(Trainer, 1946; Klump *et al.*, 1986)
Galliformes	bobwhite quail	*Colinus virgianus*	(Barton *et al.*, 1984)
Galliformes	chicken	*Gallus*	(Gray and Rubel, 1985; Saunders and Salvi, 1993)
Galliformes	Japanese quail	*Coturnix japonica*	(Niemiec *et al.*, 1994)
Galliformes	turkey	*Meleagris gallopavo*	(Maiorana and Schleidt, 1972)
Passeriformes	American robin	*Turdus migratorius*	(Konishi, 1970)
	blue jay	*Cyanocitta cristata*	(Cohen *et al.*, 1978)
	brown-headed cowbird	*Molothrus ater*	(Hienz *et al.*, 1977)
	bullfinch	*Pyrrhula*	(Schwartzkopff, 1949)
	chipping sparrow	*Spizella passerina*	(Konishi, 1970)
	common canary	*Serinus canarius*	(Okanoya and Dooling, 1987)
	common crow	*Corvus brachyrhynchos*	(Trainer, 1946)
	European starling	*Sturnus vulgaris*	(Trainer, 1946; Konishi, 1970; Kuhn *et al.*, 1982; Dooling *et al.*, 1986)
	field sparrow	*Spizella pusilla*	(Dooling *et al.*, 1979)
	fire finch	*Lagonosticta senegala*	(Dooling *et al.*, 2000b)
	great tit	*Parus major*	(Klump *et al.*, 1986; Langemann *et al.*, 1998)
	house finch	*Carpodacus mexicanus*	(Dooling *et al.*, 1978)
	house sparrow	*Passer domesticus*	(Konishi, 1970; Aleksandrov and Dmitrieva, 1992)
	pied flycatcher	*Ficedula hypolueca*	(Aleksandrov and Dmitrieva, 1992)
	red-winged blackbird	*Agelaius phoeniceus*	(Hienz *et al.*, 1977)
	slate-colored junco	*Junco hyemalis*	(Konishi, 1970)
	song sparrow	*Melospiza melodia*	(Okanoya and Dooling, 1987; 1988)
	swamp sparrow	*Melospiza georgiana*	(Okanoya and Dooling, 1987; 1988)
	western meadowlark	*Sturnella neglecta*	(Konishi, 1970)
	zebra finch	*Taeniopygia guttata*	(Okanoya and Dooling, 1987; Hashino and Okanoya, 1989)
Psittaciformes	Bourke's parrot	*Neophema bourkii*	Dooling et al. Unpublished Data
	budgerigar	*Melopsittacus undulatus*	(Dooling and Saunders, 1974; 1975; Saunders *et al.*, 1979; Saunders and Pallone, 1980; Okanoya and Dooling, 1987; Hashino *et al.*, 1988)
	cockatiel	*Nymphicus hollandicus*	(Okanoya and Dooling, 1987)
	orange-fronted conureq	Aratinga canicularis	(Wright *et al.*, 2003)
Strigiformes	African wood owl	*Strix woodfordii*	(Nieboer and Van der Paardt, 1976)
	barn owl	*Tyto alba*	(Konishi, 1970; 1973; Dyson *et al.*, 1998)
	brown fish owl	*Ketupa zeylonensis*	(Van Dijk, 1972)
	eagle owl	*Bubo*	

Order	Common Name	Genus and Species	References
	forest eagle owl	*Bubo nipalensis*	
	great horned owl	*Bubo virginianus*	(Trainer, 1946)
	long eared owl	*Asio otus*	(Van Dijk, 1972)
	mottled owl	*Strix virgata*	
	scops owl	*Otus scops*	
	snowy owl	*Nyctea scandiaca*	
	spotted wood owl	*Strix seloputo*	
	tawny owl	*Strix aluco*	
	white-faced scops owl	*Otus leucotis*	

Appendix C: Complete Table of all Behavioral Studies of Critical Ratios in Birds

Order	**Common Name**	**Genus and Species**	**References**
Columbiformes	pigeon	*Columbia livia*	(Hienz and Sachs, 1987)
Passeriformes	brown-headed cowbird	*Molothrus ater*	(Hienz and Sachs, 1987)
	common canary	*Serinus canarius*	(Okanoya and Dooling, 1987)
	European starling	*Sturnus vulgaris*	(Okanoya and Dooling, 1987)
	fire finch	*Lagonosticta senegala*	(Lohr *et al.*, 2004)
	great tit	*Parus major*	(Langemann *et al.*, 1998)
	red-winged blackbird	*Agelaius phoeniceus*	(Hienz and Sachs, 1987)
	song sparrow	*Melospiza melodia*	(Okanoya and Dooling, 1987)
	swamp sparrow	*Melospiza georgiana*	
	zebra finch	*Taeniopygia guttata*	
Psittaciformes	budgerigar	*Melopsittacus undulatus*	(Dooling and Saunders, 1975; Dooling *et al.*, 1979; Saunders *et al.*, 1979; Okanoya and Dooling, 1987; Hashino *et al.*, 1988; Hashino and Okanoya, 1989)
	cockatiel	*Nymphicus hollandicus*	(Okanoya and Dooling, 1987)
	orange-fronted conure	*Aratinga canicularis*	(Wright *et al.*, 2003)
Strigiformes	barn owl	*Tyto alba*	(Konishi, 1973; Dyson *et al.*, 1998)

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Appendix D: Fundamentals of Highway Traffic Noise

(Provided by Caltrans)

Fundamentals of Traffic Noise

The following is a brief discussion of fundamental traffic-noise concepts. For a detailed discussion, please refer to the *Technical Noise Supplement* (Caltrans 2013) available on the Caltrans Web site (http://www.dot.ca.gov/hq/env/noise).[22]

Sound, Noise, and Acoustics

Sound is a disturbance that is created by a moving or vibrating source in a gaseous or liquid medium or the elastic stage of a solid and that is capable of being detected by the hearing organs. Sound can be described as the mechanical energy of a vibrating object transmitted by pressure waves through a medium to a hearing organ, such as a human ear. For traffic sound, the medium of concern is air. *Noise* is defined as loud, unpleasant, unexpected, or undesired sound.

Sound is actually a process that consists of three components: the sound source, the sound path, and the sound receiver. All three components must be present for sound to exist. Without a source to produce sound or a medium to transmit sound-pressure waves, there is no sound. Sound must also be received; a hearing organ, sensor, or object must be present to perceive, register, or be affected by sound or noise. In most situations, there are many different sound sources, paths, and receivers, not only one of each. *Acoustics* is the field of science that deals with the production, propagation, reception, effects, and control of sound.

Frequency and Hertz

A continuous sound can be described by its *frequency* (pitch) and its *amplitude* (loudness). Frequency relates to the number of pressure oscillations per second. Low-frequency sounds are low in pitch, like the low notes on a piano, whereas high-frequency sounds are high in pitch, like the high notes on a piano. Frequency is expressed in terms of oscillations, or cycles, per second. Cycles per second are commonly referred to as Hertz (Hz) (e.g., a frequency of 250 cycles per second is referred to as 250 Hz). High frequencies are sometimes more conveniently expressed in kilo-Hertz (kHz), or thousands of Hertz. The extreme range of frequencies that can be heard by the healthiest human ears spans from 16–20 Hz on the low end to about 20,000 Hz (20 kHz) on the high end.

Sound-Pressure Levels and Decibels

The *amplitude* of a sound determines its loudness. Loudness of sound increases and decreases with increasing and decreasing amplitude. Sound-pressure amplitude is measured in units of micro-Newtons per square meter (N/m^2) , also called micro-Pascals (µPa). One µPa is approximately one-hundred billionth (0.00000000001) of normal atmospheric pressure. The pressure of a very loud sound may be 200 million ΦPa, or 10 million times the pressure of the weakest audible sound (20 µPa). Because expressing sound levels in terms of ΦPa would be cumbersome, *sound-pressure level* (SPL) is used to describe in logarithmic units the ratio of actual sound pressures to a reference pressure squared. These units are called bels, named after Alexander Graham Bell. To provide finer resolution, a bel is divided into 10 decibels (dB).

[22] http://www.dot.ca.gov/hq/env/noise/pub/TeNS_Sept_2013B.pdf

Addition of Decibels

Because decibels are logarithmic units, SPL cannot be added or subtracted by ordinary arithmetic means. For example, if 1 automobile produces an SPL of 70 dB when it passes an observer, 2 cars passing simultaneously would not produce 140 dB; rather, they would combine to produce 73 dB. When two sounds of equal SPL are combined, they produce a combined SPL 3 dB greater than the original individual SPL. In other words, sound energy must be doubled to produce a 3-dB increase. If two sound levels differ by 10 dB or more, the combined SPL is equal to the higher SPL; the lower sound level would not increase the higher sound level.

A-Weighted Decibels

SPL alone is not a reliable indicator of loudness. The frequency of a sound also has a substantial effect on how humans respond. Although the intensity (energy per unit area) of the sound is a purely physical quantity, the loudness or human response is determined by the characteristics of the human ear.

Human hearing is limited in the range of audible frequencies as well as in the way it perceives the SPL in that range. In general, the healthy human ear is most sensitive to sounds from 1,000–5,000 Hz and perceives a sound within that range as being more intense than a sound of higher or lower frequency with the same magnitude. To approximate the frequency response of the human ear, a series of SPL adjustments is usually applied to the sound measured by a sound level meter. The adjustments, referred to as a *weighting network*, are frequency-dependent.

The A-scale weighting network approximates the frequency response of the average young ear when listening to most ordinary sounds. When people make judgments of the relative loudness or annoyance of a sound, their judgments correlate well with the A-scale sound levels of those sounds. Other weighting networks have been devised to address high noise levels or other special problems (e.g., B-, C-, and D-scales), but these scales are rarely used in conjunction with highway-traffic noise. Noise levels for traffic-noise reports are typically reported in terms of A-weighted decibels (dBA). In environmental noise studies, A-weighted SPLs are commonly referred to as noise levels. Table D1 shows typical A-weighted noise levels.

Human Response to Changes in Noise Levels

Under controlled conditions in an acoustics laboratory, the trained, healthy human ear is able to discern 1-dB changes in sound levels when exposed to steady, single-frequency ("pure-tone") signals in the mid-frequency range. Outside such controlled conditions, the trained ear can detect 2-dB changes in normal environmental noise. However, it is widely accepted that the average healthy ear can barely perceive 3-dB noise level changes A 5-dB change is readily perceptible, and a 10-dB change is perceived as being twice or half as loud. As discussed above, doubling sound energy results in a 3-dB increase in sound; therefore, doubling sound energy (e.g., doubling the volume of traffic on a highway) would result in a barely perceptible change in sound level.

Table D1. Typical Noise Levels

Common Outdoor Activities	Noise Level (dBA)	Common Indoor Activities
	— 110 —	Rock band concert
Jet flyover at 300 meters (1,000 feet)		
	— 100 —	
Gas lawn mower at 1 meter (3 feet)		
	— 90 —	
Diesel truck at 15 meters (50 feet) at 80 kilometers per hour (50 miles per hour)		Food blender at 1 meter (3 feet)
	— 80 —	Garbage disposal at 1 meter (3 feet)
Noisy urban area, daytime		
Gas lawn mower, 30 meters (100 feet)	**— 70 —**	Vacuum cleaner at 3 meters (10 feet)
Commercial area		Normal speech at 1 meter (3 feet)
Heavy traffic at 90 meters (300 feet)	**— 60 —**	
		Large business office
Quiet urban daytime	**— 50 —**	Dishwasher next room
Quiet urban nighttime	**— 40 —**	Theater, large conference room (background)
Quiet suburban nighttime		
	— 30 —	Library
Quiet rural nighttime		Bedroom at night
	— 20 —	
		Broadcast/recording studio
	— 10 —	
Lowest threshold of human hearing	**— 0 —**	Lowest threshold of human hearing

Source: Caltrans 2013.

Noise Descriptors

Noise in our daily environment fluctuates over time. Some fluctuations are minor, but some are substantial. Some noise levels occur in regular patterns, but others are random. Some noise levels fluctuate rapidly, but others slowly. Some noise levels vary widely, but others are relatively constant. Various noise descriptors have been developed to describe time-varying noise levels. The following are the noise descriptors most commonly used in traffic-noise analysis.

- *Equivalent Sound Level (L_{eq})*: L_{eq} represents an average of the sound energy occurring over a specified period. In effect, L_{eq} is the steady-state sound level that in a stated period would contain the same acoustical energy as the time-varying sound that actually occurs during the same period. The 1-hour A-weighted equivalent sound level (L_{eq}[h]), is the energy average of the A-weighted sound levels occurring during a 1-hour period and is the basis for noise-abatement criteria (NAC) used by Caltrans and the FHWA.

- *Percentile-Exceeded Sound Level (L_x)*: L_x represents the sound level exceeded for a given percentage of a specified period (e.g., L_{10} is the sound level exceeded 10% of the time, L_{90} is the sound level exceeded 90% of the time).

- *Maximum Sound Level (L_{max})*: L_{max} is the highest instantaneous sound level measured during a specified period.

- *Day-Night Level (L_{dn})*: L_{dn} is the energy average of the A-weighted sound levels occurring during a 24-hour period with 10 dB added to the A-weighted sound levels occurring between 10 p.m. and 7 a.m.

- *Community Noise Equivalent Level (CNEL)*: CNEL is the energy average of the A-weighted sound levels occurring during a 24-hour period with 10 dB added to the A-weighted sound levels occurring between 10 p.m. and 7 a.m. and 5 dB added to the A-weighted sound levels occurring between 7 p.m. and 10 p.m.

Sound Propagation

When sound propagates over a distance, it changes in level and frequency content. The manner in which noise reduces with distance depends on the following factors.

- *Geometric spreading:* Sound from a small, localized source (i.e., a point source) radiates uniformly outward as it travels away from the source in a spherical pattern. The sound level attenuates (or drops off) at a rate of 6 dBA for each doubling of distance. Traffic and construction noise is not a single, stationary point source of sound. The movement of the vehicles on a highway makes the source of the sound appear to emanate from a line (i.e., a line source) rather than a point. This line source results in cylindrical spreading rather than the spherical spreading that results from a point source. The change in sound level from a line source is 3 dBA per doubling of distance.

- *Ground absorption*: The noise path between the highway and the observer is usually very close to the ground. Noise attenuation from ground absorption and reflective-wave canceling adds to the attenuation associated with geometric spreading. Traditionally, the excess attenuation has also been expressed in terms of attenuation per doubling of distance. This approximation is done for simplification only because prediction results based on this scheme are sufficiently accurate for distances of less than 60 meters (200 feet). For acoustically hard sites (i.e., those sites with a reflective surface, such as a parking lot or a smooth body of water, between the source and the receiver), no excess ground attenuation is assumed. For acoustically absorptive or soft sites (i.e., those sites with an absorptive ground surface, such as soft dirt, grass, or scattered bushes and trees, between the source and the receiver), an excess ground-attenuation value of 1.5 dBA per doubling of distance is normally assumed. When added to the geometric spreading, the excess ground attenuation results in an overall drop-off rate of 4.5 dBA per doubling of distance for a line source and 7.5 dBA per doubling of distance for a point source.

- *Atmospheric effects*: Research by Caltrans and others has shown that atmospheric conditions can have a significant effect on noise levels within 60 meters (200 feet) of a highway. Wind has been shown to be the most important meteorological factor within approximately 150 meters (500 feet) of the source, whereas vertical air-temperature gradients are more important for greater distances. Other factors such as air temperature, humidity, and turbulence also have significant effects. Receptors located downwind from a source can be exposed to increased noise levels relative to calm conditions, whereas locations upwind can have lower noise levels. Increased sound levels can also occur as a result of temperature inversion conditions (i.e., increasing temperature with elevation).

- *Shielding by natural or human-made features*: A large object or barrier in the path between a noise source and a receiver can substantially attenuate noise levels at the receiver. The amount of attenuation provided by this shielding depends on the size of the object and the frequency content of the noise source. Natural terrain features (e.g., hills and dense woods) and human-made features (e.g., buildings and walls) can substantially reduce noise levels. Walls are often constructed between a source and a receiver specifically to reduce noise. A barrier that breaks the line of sight between a source and a receiver will typically result in at least 5 dB of noise reduction. A taller barrier may provide as much as 20 dB of noise reduction.

D. Federal and State Regulations, Standards, and Policies

Federal and state regulations, standards, and policies relating to traffic noise are discussed in detail in the Protocol. A transportation project affected by the Protocol is referred to as type 1 project, which is defined in 23 CFR 772 as a proposed federal or federal-aid highway project for construction of a highway on a new location or the physical alteration of an existing highway that significantly changes the horizontal or vertical alignment or increases the number of through traffic lanes. The FHWA has clarified its interpretation of type 1 projects by stating that a type 1 project is any project that has the potential to increase noise levels at adjacent receivers. This includes projects to add interchange, ramp, auxiliary, or truck-climbing lanes to an existing highway. A project to widen an existing ramp by a full lane width is also considered to be a type 1 project. Caltrans extends this definition to include state-funded highway projects. The project alternatives evaluated in this report are considered to be a Type 1 project because they involve federal funding and adding lanes to the existing mainline highway.

Applicable federal and state regulations, standards, and policies are discussed below.

National Environmental Policy Act

NEPA is a federal law that establishes environmental policy for the nation, provides an interdisciplinary framework for federal agencies to prevent environmental damage, and contains action-forcing procedures to ensure that federal agency decision-makers take environmental factors into account. Under NEPA, impacts and measures to mitigate adverse impacts must be identified, including impacts for which no mitigation or only partial mitigation is available. The FHWA regulations discussed below constitute the federal noise standard. Projects complying with this standard are also in compliance with the requirements stemming from NEPA.

Federal Highway Administration Regulations

23 CFR 772 provides procedures for conducting highway-project noise studies and implementing noise-abatement measures to help protect the public health and welfare, supply NAC, and establish requirements for information to be given to local officials for use in planning and designing highways. Under this regulation, noise abatement must be considered for a type 1 project if the project is predicted to result in a traffic-noise impact. A traffic-noise impact is considered to occur when the project results in a *substantial noise increase* or when the predicted noise levels *approach or exceed* NAC specified in the regulation. 23 CFR 772 does not specifically define what constitutes a substantial increase or the term approach; rather, it leaves interpretation of these terms to the states.

Noise-abatement measures that are *reasonable* and *feasible* and likely to be incorporated into the project, as well as noise impacts for which no apparent solution is available, must be identified before adoption of the final environmental document for the project. Table D2 summarizes the FHWA's NAC.

Table D2. Activity Categories and Noise Abatement Criteria

Activity Category	Activity L_{eq}[h][1]	Evaluation Location	Description of Activities
A	57	Exterior	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B[2]	67	Exterior	Residential.
C[2]	67	Exterior	Active sport areas, amphitheaters, auditoriums, campgrou cemeteries, day care centers, hospitals, libraries, medical facilities, parks, picnic areas, places of worship, playgrour public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, recreation area Section 4(f) sites, schools, television studios, trails, and tra crossings.
D	52	Interior	Auditoriums, day care centers, hospitals, libraries, medica facilities, places of worship, public meeting rooms, public nonprofit institutional structures, radio studios, recording studios, schools, and television studios.
E	72	Exterior	Hotels, motels, offices, restaurants/bars, and other develop lands, properties, or activities not included in A–D or F.
F			Agriculture, airports, bus yards, emergency services, industrial, logging, maintenance facilities, manufacturing, mining, rail yards, retail facilities, shipyards, utilities (wat resources, water treatment, electrical), and warehousing.
G			Undeveloped lands that are not permitted.

[1] The L_{eq}(h) activity criteria values are for impact determination only and are not design standards for noise abatement measures. All values are A-weighted decibels (dBA).

[2] Includes undeveloped lands permitted for this activity category.

Primary consideration is given to exterior areas. In situations where no exterior activities are affected by traffic noise the interior criterion (activity category E) is used as the basis for noise abatement consideration.

California Environmental Quality Act

CEQA is the foundation of environmental law and policy in California. The main objectives of CEQA are to disclose to decision-makers and the public the significant environmental effects of proposed activities and to identify ways to avoid or reduce those effects by requiring implementation of feasible alternatives or mitigation measures. Under CEQA, a substantial noise increase may result in a significant adverse environmental effect; if so, the noise increase must be mitigated or identified as a noise impact for which it is likely that only partial (or no) mitigation measures are available. Specific economic, social, environmental, legal, and technological conditions can make mitigation measures for noise infeasible.

Traffic-Noise Analysis Protocol for New Highway Construction and Reconstruction Projects

The Protocol specifies the policies, procedures, and practices to be used by agencies that sponsor new construction or reconstruction projects. NAC specified in the Protocol are the same as those specified in 23 CFR 772. This report defines a noise increase as substantial when the predicted noise levels with project implementation exceed existing noise levels by 12 dBA -L_{eq} (h). The Protocol also states that a sound level is considered to approach an NAC level when the sound level is within 1 dB of the NAC identified in 23 CFR 772. For example, a sound level of 66 dBA is considered to approach the NAC of 67 dBA, but 65 dBA is not.

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Appendix E: Review of Pre-2007 Literature on Effects of Traffic Noise on Birds

From (Dooling and Popper, 2007)

The literature on the actual effects of traffic noise on birds is limited and the methodology is often insufficient to provide a clear correlation between traffic noise and any effects on bird physiology and/or behavior. One particular concern is that whereas there is indirect evidence that traffic noise may affect birds (e.g., Reijnen and Foppen, 1994; 1995; Reijnen *et al.*, 1995; Forman *et al.*, 2002), there are also correlated variables that could have impact such as visual stimuli, air pollution produced by autos and trucks (e.g., Llacuna *et al.*, 1996; Clench-Aas *et al.*, 2000), and changes in the physical environment around the roadways (e.g., Ferris, 1979). Differentiating among these and other variables is often difficult or impossible. While there is statistical evidence (debated by some, see below) to suggest that noise may affect birds in some way (e.g., Reijnen and Foppen, 1994; 1995; Reijnen *et al.*, 1995), there have yet to be definitive experiments that clearly isolate noise as an exclusive source of disturbance. Even when noise is implicated as a contributing factor, there are still are many variables which are poorly understood, such as noise levels at the birds (received levels), effects of frequency of disturbances (e.g., how many cars/trucks come by a bird in some time interval – (Forman *et al.*, 2002), and species. Complicating this picture even further are substantial species differences in the way that birds respond to noise and how readily they may acclimate or habituate to various disturbances (e.g., Ferris, 1979; Kuitunen *et al.*, 1998; Fernández-juricic, 2001; Slabbekoorn and Ripmeester, 2008; Slabbekoorn *et al.*, 2012).

The overall literature has been critically reviewed several times in recent years (e.g., Sarigul-Klijn *et al.*, 1997; Kaseloo, 2005; Warren *et al.*, 2006; van der Ree *et al.*, 2011; Ortega, 2012). These reviews suggest that a good portion of the literature is not relevant to the issues at hand since the literature often does not take into consideration all appropriate variables (e.g., variables other than sound) or that the publications have problems with data analysis and/or interpretation.

In one analyses, Warren *et al.* (2006) evaluated data suggesting that noise could affect bird behavior. However, the authors pointed out that while the data could be interpreted as indicating that noise may affect birds, none of the earlier work can clearly be used to reach any firm conclusions about any one species, or all species. Indeed, Warren *et al.* (2006) point out the need for very specific and highly controlled laboratory and field studies to assess how highway (or any other) noise will affect birds. Such experiments are very difficult (and expensive) to design and execute, and all other variables must be taken into consideration in design of these experiments.

The four major sets of studies considered by Warren *et al.* (2006) are helpful to understanding the issues. In one series of papers, Reijnen and colleagues (Foppen and Reijnen, 1994; Reijnen and Foppen, 1994; 1995; Reijnen *et al.*, 1995) reviewed in (Reijnen *et al.*, 1998) examined the effects of motorway traffic on breeding bird populations in the Netherlands. The investigators concluded that traffic noise has an impact on birds within several hundred meters of the road and that roadway noise lowers the extent of bird breeding near highways. The study by Reijnen and colleagues showed that when traffic noise level was constant, there was no discernable effect from visual disturbance. But when visual disturbance was kept constant, bird distribution

patterns were statistically correlated with traffic noise. Furthermore the authors noted that visual disturbance and vehicular pollutants extended outward only a short distance from the roadway, whereas both traffic noise and reduced bird densities extended outward much further. This differential effect distance approach suggests that if it is appropriately integrated into the experimental designs of future studies, it could provide more tractable means for isolating the effects of the confounding variables and better extracting focused information on noise-specific impacts.

While the data from Reijnen et al. are interesting and possibly instructive, the work has been severely criticized for poor statistical analysis and poor controls, and for lack of analysis of individual bird species (Sarigul-Klijn *et al.*, 1997) which concluded that the number of birds studied was too low for reliable statistical measures and that levels of significance used varied between study years. Sarigul-Klijn *et al*. (1997) also concluded that Reijnen et al., in reaching their conclusions, also did not consider construction as another potential point of impact on birds.

Most importantly, the Transportation Noise Control Center study (Sarigul-Klijn *et al.*, 1997) points out that Reijnen and colleagues pooled all of their data so that they presented a possible effect on all species, rather than determine whether there are species-specific effects. The importance of the species variability in response to noise (and other factors) has been emphasized in several other studies which have shown variability in whether different species respond to noise or not (e.g., Clark and Karr, 1979; Ferris, 1979; Van der Zande *et al.*, 1980; Kuitunen *et al.*, 1998; Fernández-juricic, 2001; Peris and Pescador, 2004). Indeed, lack of consideration of species variability in life style is also the basis for the poor generality of the FWS (2006) recommended procedures for analysis of the effects of sounds on spotted owls and marbled murrelets.

In another study, Stone (2000) did transects to determine bird populations over a wide range of land use types. The results led to the suggestion that there is a marked decrease in bird populations in noisier areas, despite the specific land use. However, Warren *et al.*, (2006) criticized the Stone (2000) study and pointed out that while noise was one variable that could have affected bird populations in some types of land use and not in others, Stone (Stone, 2000) did not do a multi-factor analysis to determine if other habitat issues, such as whether there were also differences ground surface, vegetative type, or other variables that could have altered a bird's behavior.

A more convincing case that traffic noise may affect birds is a study by Forman et al. (Forman *et al.*, 2002) which looked at the presence of five species of grassland bird populations at different distances from roadways in and around Boston. The authors argue that there is an effect on density of species studied by roadway noise, but that the extent of the effect, in terms of decreased populations at different distances, varied depending upon the level of traffic on the road. They found that when traffic was less than 8,000 vehicles/day there was no effect on grassland bird populations. In areas with from 8,000-15,000 vehicles per day, there was no effect on population levels per se, but there were fewer breeding birds up to 400 m from the road. Bird presence and breeding was decreased at up to 700 m from the roadway when there were from 15,000-30,000 vehicles per day, whereas this distance increased to 1,200 m for more than 30,000 vehicles per day (a multilane highway). While the authors conclude that noise may be the major factor affecting these grassland species, but that other environmental variables such as visual

signals, air pollutants, and lack of prey near the roadways may help explain the decline in bird populations. Clearly, direct experimental evidence of effects of increased chronic noise of different levels and sound spectra (Lee and Fleming, 1996) is needed to confirm this hypothesis (also see Warren *et al.*, 2006).

Still, it is important to recognize that the results from Forman *et al.* (2002) may not be applicable to all species, or in all situations. For example, Peris and Pescador (2004) examined the effects of low, medium, and high traffic volumes on bird populations of 20 passerine species in pasture-woodland environments near several roads in western central Spain. While it is hard to specifically compare results between the two studies since Peris and Pescador (2004) did not define road density in terms of actual number of vehicles/day, the different results are instructive. In contrast to Forman et al. (Forman *et al.*, 2002), Peris and Pescador (2004) provided sound level measures at distances of 50-100 m from the roadways. They reported that the high traffic volume area had sound levels of 69±5 dB, medium density 46±3 dB, and low density at 36±2 dB (it was not indicated if this was dB SPL or dBA). Peris and Pescador (2004) showed that there were differences between the number of birds and the extent of breeding populations in each of the three areas, but the differences varied by species. In effect, no one pattern of bird presence was appropriate for all of the species studied over the two year period.

For example, corn bunting (*Miliaria calandra*), rock sparrow (*Petronia petronia*), and house sparrow (*Passer domesticus*) had a higher breeding density in the high traffic (noisier) environment than they did in the low traffic volume areas. In contrast, breeding density was higher for wheatear (*Oenanthe* sp.) in low and moderate traffic areas (quieter) than in high traffic areas. The authors concluded that 55% of the species did not show any difference in breeding density between the three noise level sites, whereas other birds did show statistically significant differences. The authors suggest that the differences in responses of the various species may depend on hearing sensitivity of the species, with birds that have more sensitive hearing showing greater avoidance of road noise than birds with poorer hearing.

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Appendix F: Recommendations for Research to Refine Future Guidance

The three classes of potential effects of traffic noise on birds: (1) behavioral and/or physiological effects; (2) damage to hearing from acoustic over-exposure; and (3) masking of communication signals. All of these can cause dynamic behavioral, and population effects. These three classes of potential effects lead to separate, *but overlapping*, recommendations for future work (see Table F1 and Table F2). Some of this work is at high priority while other work is of lower priority depending on the criteria for making decisions. High priority could be to go for those issues that can be tackled by efficiency of data collection and the precision of the results (e.g., noise exposure studies in the laboratory), or, at by taking on the problem that extends the furthest from the roadway (e.g., field studies of stress and disturbance effects at distances far beyond those at which hearing damage and masking from traffic noise might occur). Or highest priority could be assigned to some combination of studies which give the greatest potential value for moving us forward to better and more useful *interim* guidelines. Experiments that can quickly improve the *interim* guidelines are given a higher priority than longer-term (and often more difficult) experiments that may not refine the *interim* guidelines efficiently. It should be noted that while not always stated explicitly, all studies should be done on several species.

7) Stress and physiological effects:[23]
   a) Obtain a definitive answer to the question of whether traffic noise alone can cause stress, physiological reactions, and disturbances in social behavior in birds by using artificial traffic noises broadcast in large areas while birds (preferably captive) are monitored for stress indices (low priority).
   b) Conduct studies comparatively to determine if stress effects are species specific (low priority).
   c) Conduct studies on birds of different ages and with different degrees of experience with loud noises to determine if experience is a factor in stress-related impacts (low priority).

8) Acoustic over-exposure effects:
   a) Conduct lab experiments to definitively rule out the possibility that continuous loud traffic noise can damage avian hearing (low priority).
   b) Examine effects of different levels of continuous noise on temporary and permanent hearing loss in different bird species (high priority).
   c) Examine effects of impulsive noise such as that produced by construction equipment and pile driving on hearing loss in different bird species. Consider a range of variables including: the intensity of the noise, the number of impulses, inter-pulse interval, and effects of different "rest periods" between pulses on hearing loss. Also include combinations of continuous traffic noise and impulse noises since some mammalian data suggest a synergistic effect (high priority).

9) Masking effects:
   a) Extend what is known about masking effectiveness of traffic noise on the vocalizations of birds by conducting behavioral tests with a wider range of individual and species

[23] It should be noted that precise definition of the questions and issues of the effects of traffic noise on birds should be developed with the guidance of individuals who are expert on avian endocrinology and the literature on this topic.

vocalizations, different types and levels of traffic noise, traffic noises filtered through various habitats, and recorded at various distances from the roadway (high priority)

b) Assemble current data or generate new data on vocalizations of endangered species including types, levels, preferred singing location preferences, habitat characteristics, territory size, effects of habitat characteristics on vocalization and noise transmission. This will allow precise modeling of the masking effects of traffic noise acoustic communication (high priority).
c) Obtain ABR measures of hearing (audiogram) and masking (critical ratios) in endangered species to determine how well they conform to the emerging model of masking of vocalizations by noise which, to date, is based primarily on laboratory species of birds (high priority).
d) Develop a generalized quantitative model for estimating communication distance based on masking data, habitat characteristics, territory size, the bird's singing position preferences, and different traffic noise profiles (high priority).

10) Dynamic behavioral effects[24]
   a) Evaluate population dynamic shifts (i.e., population range, predator prey relationships, etc.) based on increases in ambient traffic noise and construction related activities.
   b) Evaluate any secondary effects of implementing adaptations in order to avoid masking. How does this interact with other life-cycle activities such as mate attraction, prey identification, territory size, etc.
   c) Understand behavioral indicators of harassment or stress such as flushing from a nest, territorial behaviors, etc. associated with noise.

The recommendations are summarized in Tables F1 and F2. Table F1 presents the data in terms of examining the effects in terms of specific sound types.

Table F1: Research recommendations based on interim guidelines

Noise Source Type	Hearing Damage	Masking	Behavioral/ Physiological
Single Impulse (e.g., Blast)	Expose multiple species to impulsive noises (at different levels/distances) and measure hearing loss & recovery.	Not applicable	Examine animals post exposure for signs of stress (e.g., droppings, etc.)
Multiple Impulse (e.g., jackhammer, pile driver)	Expose multiple species to multiple strikes (at different levels/distances/intervals) and measure hearing loss and recovery.	In multiple species, examine masking by low level noises from multiple strikes to compare with results from continuous noise masking(Lab study)	Examine animals post exposure for signs of stress (e.g., droppings, etc.)
Non-Strike Continuous (e.g., construction noise)	Not applicable	In multiple species, examine masking by low level noises from multiple strikes to compare with results from continuous noise masking(Lab study)	Examine animals post exposure for signs of stress (e.g., droppings, etc.)
Traffic and Construction Noise	Not applicable	In multiple species, examine masking by low level traffic and construction noises to compare with results from continuous noise masking(Lab study)	Examine animals post exposure for signs of stress (e.g., droppings, etc.)
Alarms (97 dB/100 ft)	NA	NA	Future research

[24] Get input from experts in behavioral ecology on the types of population effects that might be expected.

Table F2: Additions to basic science data to inform decisions on interim guidelines and future analyses	
Topic	**Method**
Audiograms in Birds	Measure hearing thresholds in a variety of species using the ABR(lab & field)
Masked Thresholds in Birds	Measure masked thresholds and critical ratios in a variety of (endangered) species using the ABR(lab & field)
Vocalization & Communication Distance	Review literature for description of vocalizations, territory size, and communication range, young learning songs, female choice in breeding
Acoustic Communication Model	Develop a model that combines habitat characteristics (e.g., sound transmission), vocalization characteristics (e.g., spectrum, intensity, etc.) and masked thresholds to refine estimates of the effects of masking by noise on communication.
Attenuation/Avoidance/Minimization/Mitigation Methods	Evaluate ways which may inform decisions regarding equipment use, attenuation methods, avoidance, minimization/mitigation methods.

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Appendix G: A History of the 60 dBA Criterion

In 1987, a biologist, John Rieger, developed a criterion for a California highway project by measuring noise levels at the nests of birds along a highway. On average, these levels approximated 60 dBA (Barrett, 1996). According to Barrett, Rieger assumed that if birds were successfully breeding, then this noise level is, by definition, not detrimental to the birds. Unaware of this work, and completely independently, Dooling also provided the California Fish and Wildlife Service with a noise level of 60 dBA for traffic noise that would begin to raise concerns about potential masking of communication sounds between birds by traffic noise. Barret's number came from actual observations of birds nesting in noisy areas near a highway. Dooling's number came from an auditory model that calculated whether noise levels from traffic rose above ambient noise levels enough to affect acoustic communication between two birds. In neither case was this number intended to set a precedent or become a standard for noise-impact mitigation. The level of 60 dBA for traffic noise only applies, at best, under a narrow range of specific conditions having to with the sound-affecting aspects of the habitat, the species life style and dependence on acoustic communication, the level of ambient noise without any traffic noise, as well as whether the species' predators use acoustic signals to locate their prey. The use of one number like 60 dBA provides only a crude and probably conservative estimate. A precise answer would require the information just discussed as well as information about the level and spectrum of the ambient noise, of the traffic noise, and of the bird's vocalizations.

Nevertheless, it appears that the 60 dBA criterion has been inappropriately used in many reports over the past 25 years as a hard and fast rule regarding the effects of highway and other anthropogenic noise on birds. The evidence today clearly shows that the application of this criterion to construction noise is likely to be far too conservative and unnecessarily restrictive. There are several reasons for this conclusion: (1) birds do not hear as well as humans at low frequencies which contain the bulk of energy in traffic noise; (2) bird vocalizations are at higher frequencies than traffic noise; (3) the use of the A scale on the sound level meter which mirrors human hearing, as opposed to bird hearing, overestimates the effects of traffic noise on bird hearing because traffic and construction noises are predominantly low frequency; and (4) birds, like humans, can and do employ a number of short term behavioral strategies for hearing in noise such as turning their heads, changing height or location, raising their voice, and timing their communication to coincide with periods of low noise.

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