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BEFORE THE
PUBLIC SERVICE COMMISSION OF WISCONSIN

Application of Highland Wind Farm, LLC, for a Certificate of Public Convenience and Necessity To Construct a 102.5 Megawatt Wind Electric Generation Facility and Associated Electric Facilities, to be Located In the Towns of Forest and Cylon, St. Croix County, Wisconsin	Docket No. 2535-CE-100

Ex.-CW-Cook-3

Please enter the attached exhibit, Ex.-CW-Cook-3, *Personal and situational variables associated with wind turbine noise annoyance,* by David S. Michaud, et al. J. Acoust. Soc. Am. 139 (3), March 2016.

Personal and situational variables associated with wind turbine noise annoyance

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The possibility that wind turbine noise (WTN) affects human health remains controversial. The current analysis presents results related to WTN annoyance reported by randomly selected participants (606 males, 632 females), aged 18–79, living between 0.25 and 11.22 km from wind turbines. WTN levels reached 46 dB, and for each 5 dB increase in WTN levels, the odds of reporting to be either very or extremely (i.e., highly) annoyed increased by 2.60 [95% confidence interval: (1.92, 3.58), $p < 0.0001$]. Multiple regression models had R^2's up to 58%, with approximately 9% attributed to WTN level. Variables associated with WTN annoyance included, but were not limited to, other wind turbine-related annoyances, personal benefit, noise sensitivity, physical safety concerns, property ownership, and province. Annoyance was related to several reported measures of health and well-being, although these associations were statistically weak ($R^2 < 9\%$), independent of WTN levels, and not retained in multiple regression models. The role of community tolerance level as a complement and/or an alternative to multiple regression in predicting the prevalence of WTN annoyance is also provided. The analysis suggests that communities are between 11 and 26 dB less tolerant of WTN than of other transportation noise sources.
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I. INTRODUCTION

One of the most widely studied responses to environmental noise is community annoyance. There is a large body of social and socio-acoustical research spanning over 50 years which relates to the impact of noise on individuals and communities. Studies using socio-acoustic surveys have consistently shown an association between long-term average noise levels and the prevalence of reporting a high level of noise annoyance. The "*highly annoyed*" classification refers to a social survey question on noise annoyance with a

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response in the top 27%–29% on an anchored numerical scale or in the top two categories on a five point adjectival scale (Schultz, 1978), hereafter referred to as annoyance. The R^2 for models of WTN annoyance as a function of calculated long-term energy equivalent noise level alone varies from study to study, although it is often below 20%, confirming that the expression of annoyance is influenced by more than noise levels alone (Job, 1988). Long-term noise annoyance, and more specifically the change in the percentage of a community reporting to be highly annoyed by noise, has been utilised as a health endpoint in environmental assessments (Michaud *et al*., 2008a). The support for this is partially based on the possible association between high annoyance and other health effects (Niemann *et al*., 2006; World Health Organization, 2011). The World Health Organization (WHO) has recently quantified the burden of disease associated with long term high annoyance towards environmental noise (WHO, 2011). Several studies have found statistical associations between high degrees of annoyance toward noise and self-reported health effects that include, but are not limited to, migraines, heart disease, diabetes, and hypertension (Basner *et al*., 2014; Michaud *et al*., 2008b; Niemann *et al*., 2006), with these associations also reported in wind turbine studies (Pawlaczyk-Łuszczyńska *et al*., 2014; Pedersen *et al*., 2009). Annoyance need not be part of the causal chain to account for the aforementioned associations with health effects; rather, it may act as an intermediary variable between exposure and health (European Network on Noise and Health, 2013).

In comparison to the scientific literature that exists for other sources of environmental noise, there are few peer-reviewed field studies that have investigated the community response to modern wind turbines (Kuwano *et al*., 2014; Krogh *et al*., 2011; Mroczek *et al*., 2012; Nissenbaum *et al*., 2012; Pawlaczyk-Łuszczyńska *et al*., 2014; Pedersen and Persson Waye, 2004, 2007; Pedersen *et al*., 2009; Shepherd *et al*., 2011; Tachibana *et al*., 2012). The studies that have been conducted to date differ in terms of their design and evaluated endpoints. Common features include reliance upon self-reported endpoints, modeled levels of wind turbine noise (WTN), and/or proximity to wind turbines as the explanatory variable for the observed community response. Despite the small number of unique epidemiological studies published in the peer-reviewed wind turbine literature, the association between calculated WTN and self-reported community annoyance has been one of the more robust observations. A general conclusion from these studies is that annoyance increased with increasing WTN levels (or reduced proximity to wind turbines) (Shepherd *et al*., 2011) and that over and above WTN levels, the exposure-response relationship was influenced by attitudes towards wind turbines, economic incentives and population density (Pedersen and Persson Waye, 2004, 2007; Pedersen *et al*., 2009).

The present paper provides two multiple regression models for WTN annoyance. In the first *unrestricted* model, the purpose was to assess the variables that, in addition to WTN levels, have the strongest overall association with WTN annoyance. As such, there was no *a priori* exclusion of variables that may be viewed as a response to wind turbine operations (e.g., window closing behaviour, annoyance towards shadow flicker, hearing the wind turbines, etc.). Variables are selected only on the basis of the strength of their statistical association with WTN annoyance. In contrast, a second *restricted* model of community annoyance is also presented wherein, with the exception of WTN exposure, the aforementioned variables, which may be considered to more likely reflect a reaction to wind turbine operations, are not considered in the model, regardless of their statistical association with annoyance. This restricted model may yield information that could serve to identify annoyance mitigation measures, over and above a reduction in WTN levels.

Even with a restricted analysis, complex multiple regression models do not readily afford comparisons to other studies that may not have considered the same variables. The Appendix provides a more parsimonious analysis that permits the prediction of WTN annoyance by calculating community tolerance to WTN. An assessment based on community tolerance readily permits comparisons between *all* field studies. The only requirement is that each study must document the exposure-response relationship between the prevalence of high annoyance and increasing noise levels.

II. METHODS

A. Sample design

1. Target population, sample size and sampling frame strategy

The study design, target population, final sample size, allocation of participants as well as the sampling strategy has been described by Michaud *et al*. (2013) and Michaud *et al*. (2016b). Briefly, the study locations were drawn from areas in southwestern Ontario (ON) and Prince Edward Island (PEI) where there were a sufficient number of dwellings within the vicinity of wind turbine installations. There were 2004 potential dwellings identified from the ON and PEI sampling regions, which included 315 and 84 wind turbines, respectively. All turbines had three pitch controlled rotor blades (~80 m diameter) upwind of the tower. The wind turbine electrical power outputs ranged between 660 kW to 3 MW (average 2.0 ± 0.4 MW). Turbine hub heights were predominantly 80 m. All identified dwellings within approximately 600 m from a wind turbine and a random selection of dwellings between 600 m and 11.22 km were selected, from which one person per household between the ages of 18 and 79 years was randomly chosen to participate. Several factors influenced the determination of the final sample size, including having adequate statistical power (Michaud *et al*., 2016b; Michaud *et al*., 2016c) to assess the study objectives, and the time required for collection of data, as influenced by factors such as the length of the interview and the time needed to collect the physical measures.

This study was approved by the Health Canada and Public Health Agency of Canada Review Ethics Board (Protocols #2012–0065 and #2012–0072).

B. Calculating wind turbine and nighttime background sound pressure levels at dwellings

A detailed description of the approach applied to sound pressure level modeling [including background nighttime sound pressure (BNTS) levels] is presented separately (Keith

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et al., 2016a,b). Briefly, sound pressure levels were estimated at each dwelling using both ISO 9613-1 (ISO, 1993) and ISO 9613-2 (ISO, 1996) as incorporated in the commercial software CadnaA version 4.4 (Datakustik®, 2014). The calculations included all wind turbines within a radius of 10 km, and were based on manufacturers' octave band sound power spectra at 8 m/s standardized wind speed and favourable sound propagation conditions. The few dwellings beyond this distance were assigned the same calculated WTN value as dwellings at 10 km. The manufacturers' data were verified for consistency using on-site measurements of wind turbine sound power (Keith *et al*., 2016a). Unless otherwise stated, all decibel references are A-weighted.

The BNTS levels were calculated according to the Alberta noise regulations [Alberta Utilities Commission (AUC), 2013], which estimates ambient noise levels in rural and suburban environments. Estimated levels can range from 35 to 51 dB, based on dwelling density and calculated distance to heavily travelled roads or rail lines. In ON, road noise for the six lane concrete 401 Highway was calculated using the U.S. Traffic Noise Model (United States Department of Transportation, 1998) module in the CadnaA software. This value was used if it exceeded the Alberta noise estimate (Keith *et al*., 2016b).

C. Data collection

1. Questionnaire

A detailed description of the questionnaire development, including content, pilot testing, administration, and the approaches used to enhance participation, have been described in detail by Michaud *et al*. (2013), Michaud *et al*. (2016b), and Feder *et al*. (2015). The questionnaire included modules on basic demographics, noise annoyance, wind turbine perceptions (including concern for physical safety), health effects, quality of life, sleep quality, perceived stress, lifestyle behaviours, and prevalence of chronic diseases (Statistics Canada, 2014).

The official title of the study, *Community Noise and Health Study* (CNHS), was used throughout all data collection phases as a means of masking the true intent of the study, which was to assess the association between wind turbines and health. This approach is commonly used in epidemiological studies to avoid a disproportionate contribution from any group that may have distinct views towards the study subject, such as wind turbines. At multiple times of the day, 16 Statistics Canada trained interviewers conducted in-person home interviews including physical measures data collection between May 2013 and September 2013, in southwestern ON and PEI. Potential participants were informed that the purpose of the survey was to investigate community noise and the potential impact on health. Once a roster of all adults, 18 to 79 years, living in the dwelling was compiled, a computer algorithm selected one adult per dwelling. No substitution was permitted under any circumstances. Participants were not compensated for their participation.

2. Defining "highly" annoyed

Annoyance toward WTN, road traffic, aircraft and rail noise was assessed using the five-point adjectival scale as per ISO/TS (ISO, 2003a) after it was confirmed that the noise source of interest was audible (Michaud *et al*., 2016b). For each source of noise heard, participants were then asked to respond to the following question "*Thinking about the last year or so, when you are at home, how much does noise from [SOURCE] bother, disturb or annoy you?*" Participants were asked to select one of the following response categories: "*not at all*," "*slightly*," "*moderately*," "*very*," or "*extremely*." Participants that reported they did not hear a particular source of noise were classified into a "*Do not hear*" group and retained in the analysis. The analysis of annoyance was performed after collapsing the response categories into two groups (i.e., "*highly annoyed*" and "*not highly annoyed*"). As per ISO/TS (ISO, 2003a), participants reporting to be either "*very*" or "*extremely*" annoyed were treated as "*highly annoyed*" in the analysis. Consistent with Pedersen *et al*. (2009), the "*not highly annoyed*" group was comprised of participants who did not hear the source or indicated that they were "*not at all*," "*slightly*," and "*moderately*" annoyed by the source. A similar approach was used for the assessment of highly sleep disturbed and highly concerned for physical safety from having wind turbines in the area.

D. Statistical methodology

The analysis for categorical outcomes closely follows the description as outlined in Michaud *et al*. (2013), which provides a summary of the pre-data collection study design, and objectives, as well as proposed data analysis. Final A-weighted WTN categories were defined as follows: {<25; [25–30); [30–35); [35–40); and [40–46]}. As a first step to develop the best predictive model for WTN annoyance, univariate logistic regression models were carried out with WTN category as the exposure of interest, adjusted for province and a predictor of interest. It should be emphasized that variables considered in the univariate analysis have been previously demonstrated to be related to the modeled endpoint and/or considered by the authors to conceptually have a potential association with the modeled endpoint. The analysis of each variable only adjusts for WTN category and province, therefore interpretation of any individual relationship must be made with caution.

Multiple logistic regression models to identify variables associated with WTN annoyance were developed using stepwise regression with a 20% significance entry criterion for predictors (based upon univariate analyses) and a 10% significance criterion to remain in the model. The stepwise regression was carried out in three different ways: (1) the base model included exposure to WTN category and province, (2) the base model included exposure to WTN category, province, and an adjustment for participants who reported receiving personal benefit from having wind turbines in the area, and (3) the base model included exposure to WTN category and province, conditioned on those who reported receiving no personal benefit. In all models, WTN category was treated as a continuous variable. The current model aimed to identify variables that have the strongest overall association with annoyance.

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All models were adjusted for provincial differences. Province was initially assessed as an effect modifier. Since the interaction was not statistically significant for any of the regression models, province was treated as a confounder in the models with associated adjustments, as required. In cases when cell frequencies were small (i.e., <5) in logistic regression models, exact tests were used as described in Agresti (2002) and Stokes *et al.* (2000). The Nagelkerke pseudo R^2 and Hosmer-Lemeshow (H-L) *p*-value were reported for all logistic regression models.

Statistical analysis was performed using Statistical analysis system version 9.2 (SAS Institute Inc., 2014). A 5% statistical significance level was implemented throughout unless otherwise stated. In addition, Bonferroni corrections were made to account for all pairwise comparisons to ensure that the overall Type I (false positive) error rate was less than 0.05.

III. RESULTS

A. Wind turbine sound pressure levels at dwellings, response rates, and sample characteristics

Calculated outdoor sound pressure levels reached 46 dB. Calculations are representative of typical worst case long term (1 year) average WTN levels. Of the 2004 potential dwellings, 1570 addresses were considered to be valid dwellings, from which 1238 occupants agreed to participate in the study (606 males, 632 females). This produced a final calculated response rate of 78.9%. The 434 dwellings that were found to be out-of-scope was anticipated based on previous surveys carried out in rural Canadian areas and on Census data forecasting a higher out-of-scope dwelling rate in PEI compared to ON. A characterisation of the out-of-scope locations is provided in Michaud *et al.* (2016b).

The study sample was found to be relatively homogenous with some minor differences found with respect to age, employment, type of home and home ownership. Self-reported prevalence of illnesses, chronic diseases, noise sensitivity and reporting to be highly sleep disturbed in any way for any reason were all found to be statistically equivalent across WTN categories (Michaud *et al.*, 2016b).

B. Effects of WTN on annoyance

The analysis of self-reported annoyance towards several features associated with wind turbines (i.e., visual impacts, shadow flicker, vibrations, and blinking lights) in relation to WTN levels has been presented in a separate paper by Michaud *et al.* (2016b). In addition to reporting the prevalence of annoyance toward WTN in general, Michaud *et al.* (2016b) also provided an analysis of the WTN annoyance as a function of location (indoors, outdoors), time of day (morning, afternoon, evening, nighttime), and season (summer, fall, winter, spring). The focus of the current analysis is the characterization of the variables that are related to WTN annoyance in general, hereafter referred to as WTN annoyance.

1. Univariate analysis of variables related to WTN annoyance

The base model included WTN category and province as explanatory variables with regard to WTN annoyance. The Nagelkerke pseudo R^2 for this model was 12% (see supplemental material[1]). The R^2 was less than 10% with only WTN levels in the model.

Variables related to WTN annoyance after accounting for WTN level and province in the logistic regression models are presented in the supplemental material.[1] Some of the notable variables that were related to WTN annoyance in these univariate analyses included property ownership, household complaint regarding WTN, noise sensitivity, perceived stress, self-reported sleep disturbance, annoyance with other wind turbine features (e.g., blinking lights), window closing behaviour, and concern for physical safety from having wind turbines in the area (see supplemental material[1]). Many of the self-reported illnesses (e.g., migraines, tinnitus, dizziness, chronic pain, etc.) were statistically related to WTN annoyance; however, chronic conditions that were reported to have been diagnosed by a health care professional tended to not be related to WTN annoyance (see supplemental material[1]).

The relationship between WTN annoyance and the three validated modules incorporated in the study questionnaire: WHOQOL-BREF (Skevington *et al.*, 2004; WHOQOL Group, 1998), Perceived Stress Scale (PSS) (Cohen *et al.*, 1983), and the Pittsburgh Sleep Quality Index (PSQI) (Buysse *et al.*, 1989) was assessed in the CNHS. Decreased quality of life, higher perceived stress and scores on the PSQI were all associated with higher odds of reporting to be highly annoyed by WTN (see supplemental material[1]).

Modeled BNTS levels ranged between 35 and 61 dB in the sample (Keith *et al.*, 2016b). Average BNTS was highest in the WTN group [30–35) dB and lowest in areas where modeled WTN levels were between 40 and 46 dB. BNTS level was not significantly associated with WTN annoyance and the odds of WTN annoyance did not change as a function of BNTS level. Furthermore, after accounting for BNTS levels, WTN annoyance was still significantly associated with WTN levels ($p < 0.0001$) (see supplemental material[1]).

2. Multiple logistic regression model for WTN annoyance

As noted in Sec. II D, variables considered in the multiple regression model had to be significant at the 20% level and be conceptually related to WTN annoyance. Table I provides a summary of the variables that met these conditions.

The final multiple logistic regression models for the three approaches listed in the statistical methodology section yielded similar results. The predictive strength of the three final models was close to 60%. For these reasons, only the results from the first unrestricted multiple logistic regression model are shown in Table II.

WTN annoyance was strongly related to closing bedroom windows to reduce noise during sleep when WTN was identified as the source. Even after adjusting for the other variables in the final model, those who closed their window

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TABLE I. Variables conceptually related to WTN annoyance and statistically significant at the 20% level.

Variable	p-value
Income	0.182
Property ownership[a]	0.007
Personal benefit[a]	<0.0001
At least 1 turbine on property	0.003
Complaint about wind turbine noise	<0.0001
Number of years turbines audible	0.090
Sensitivity to noise[a]	<0.0001
Audible WTN	<0.0001
Audible road traffic[a]	0.150
Ability to see turbines from property[a]	0.153
Visual annoyance to wind turbines	<0.0001
Annoyance with blinking lights	<0.0001
Shadow flicker annoyance	<0.0001
Notice vibrations during turbine operations	<0.0001
Annoyance to vibrations/rattles	<0.0001
Concerned about physical safety[a]	<0.0001
Bedroom window type[a]	0.011
Bedroom on quiet side[a]	0.125
Calculated volume of bedroom (1000 ft^3)[a]	0.049
Closing bedroom window to block outside noise during sleep	<0.0001
Closure of bedroom window due to road traffic	0.123
Closure of bedroom window due to wind turbines	<0.0001
Migraines	<0.0001
Dizziness	<0.0001
Tinnitus	<0.0001
Chronic pain	<0.0001
Medication for high blood pressure	0.191
Diagnosed sleep disorder	0.115
Restless leg syndrome	0.023
Self-reported sleep disturbance	<0.0001
Rated quality of life	0.016
Score on PSQI (categorical and range 0–21)	<0.0001
Physical Health domain (range 4–20)	<0.0001
Psychological domain (range 4–20)	0.049
Environment domain (range 4–20)	<0.0001
Perceived Stress Scale (range 0–37)	0.014

[a]Tested in the restricted multiple regression model.

due to WTN had 8 times higher odds of being annoyed by WTN compared to those who did not need to close their window for this reason. In all three models, this variable was the first factor to enter the multiple logistic regression model and the corresponding Nagelkerke R^2 in the base models increased from approximately 11% to 41%. The variables that added the remaining 17% to the R^2 included, but were not limited to, other wind turbine related annoyances (i.e., blinking lights on the nacelle of the wind turbines, visual impact, and vibrations), noise sensitivity, concern about physical safety from having wind turbines in the area, and self-reported sleep disturbance over the last year.

It was also of interest to develop a model of community annoyance restricted to the variables from Table I that are not likely to reflect a reaction to wind turbine operations. Such a model may yield information that could serve to identify annoyance mitigation measures, which are over and above a reduction in WTN levels. Variables that were considered included, but were not limited to, type of dwelling, facade type, property ownership, type of windows, bedroom location within dwelling, self-reported size of bedroom (e.g., volume), presence of air conditioner in the dwelling, visibility of wind turbines from anywhere on the property, other noise sources that the participant reported hearing (e.g., road traffic, railway, aircraft), receiving personal benefits, concern for physical safety associated with having wind turbines in the area, noise sensitivity, and BNTS levels. Income was not considered for inclusion in the restricted regression model because it would have reduced the sample size from 1129 to 968. Furthermore, income was not statistically significant in the unrestricted multiple regression model. Although the variables considered were different from the unrestricted model, the same stepwise procedure as explained in Sec. II D was carried out to develop the restricted multiple logistic regression model.

Table III presents the results for the final restricted multiple logistic regression model where personal benefits was considered for entry into the model. Variables that entered the final model and were associated with higher odds of being annoyed to WTN included concern for physical safety from having wind turbines in the area, noise sensitivity, personal benefits, window type, dwelling ownership, and audibility of road traffic. Participants with a high concern for their physical safety had 14 times higher odds of being annoyed by WTN [95% confidence interval (CI): (7.71, 26.96)]. Participants who did not receive personal benefits had 12 times higher odds of being annoyed by WTN [95% CI: (1.66, 94.25)]. Participants reporting to have single and double pane windows in their bedroom had statistically similar odds of being highly annoyed to WTN ($p = 0.742$); and both had lower odds of being annoyed to WTN compared to those with triple pane windows ($p < 0.03$, in both cases). Participants who did not hear road traffic ($p = 0.026$) had higher odds of being highly annoyed to WTN. The final model had an R^2 of 40% (Table III).

IV. DISCUSSION

The community response to WTN reported in this study was found to be statistically related to A-weighted WTN levels. In other words, the prevalence of reporting to be very or extremely (i.e., highly) annoyed by WTN increased from 2.1% to 13.7% when sound pressure levels were below 30 dB compared to [40–46] dB, respectively. Although statistically significant, the association between WTN levels and annoyance was found to be rather weak ($R^2 = 9\%$). The R^2 substantially improved after considering annoyance due to other wind turbine related features such as the visual impact of wind turbines, the blinking lights on the nacelle used to alert aircraft, and the perception of vibrations during wind turbine operations. The self-reported high concern about physical safety from having wind turbines in the area was found to be significantly related to WTN annoyance. This finding is reminiscent of the general observation from community noise research that fear of a noise source may be the most important nonacoustic variable related to annoyance (Fields, 1993; Miedema and Vos, 1998). van den Berg *et al.* (2015) also

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TABLE II. Multiple logistic regression model (unrestricted) for WTN annoyance.

Variable	Groups in variable[a]	Multiple logistic regression model ($n = 934$, $R^2 = 0.58$,[c] H-L,[d] $p = 0.702$)		Order of entry into model: R^2 at each step
		OR(CI)[b]	p-value	
WTN (dB)[e]	Continuous	2.38 (1.42, 3.99)	0.001	Base: 0.11[f]
Province	ON/PEI	4.98 (1.15, 21.58)	0.032	Base: 0.11[f]
Closure of bedroom window due to wind turbines	Yes/no	8.45 (3.67, 19.46)	<0.0001	Step 1: 0.41
Annoyance with blinking lights	High/low	3.26 (1.40, 7.56)	0.006	Step 2: 0.50
Annoyance with vibrations/rattles	High/low	3.99 (1.22, 13.07)	0.023	Step 3: 0.52
Visual annoyance to wind turbine	High/low	2.77 (1.22, 6.29)	0.015	Step 4: 0.53
Self-reported sleep disturbance[g]	High/low	2.93 (1.27, 6.77)	0.012	Step 5: 0.55
Closure of bedroom window due to road traffic	Yes/no	0.42 (0.17, 1.05)	0.063	Step 6: 0.56
Sensitivity to noise	High/low	2.11 (0.97, 4.59)	0.061	Step 7: 0.57
Concerned about physical safety	High/low	2.56 (1.08, 6.07)	0.033	Step 8: 0.57
Complaint about wind turbines	Yes/no	3.22 (0.85, 12.20)	0.085	Step 9: 0.58

[a]Where a reference group is not specified it was taken to be the last group.
[b]Odds ratio (OR) and 95% confidence interval (CI) based on logistic regression model; an OR > 1 indicates that annoyance levels were higher, relative to the reference group.
[c]The Nagelkerke pseudo R^2 indicates how useful the explanatory variables are in predicting the response variable.
[d]H-L: Hosmer-Lemeshow test, $p > 0.05$ indicates a good fit.
[e]WTN level is treated as a continuous scale in the logistic regression model, giving an overall OR for each unit increase in WTN level, where a unit reflects a 5 dB WTN category.
[f]Note that the results of the base model differ from the supplemental material (see footnote 1) and Table III due to sample size differences.
[g]Evaluates the magnitude of reported sleep disturbance for any reason over the previous year while at home.

reported that self-reported worry about a noise source was strongly correlated to noise annoyance from that source.

Noise sensitivity was found to be a significant predictor of WTN annoyance in the current study—a finding that is consistent with previously published community noise research (Guski, 1999; Miedema and Vos, 2003), including WTN studies (Janssen *et al.*, 2011). Despite the influence that concern for physical safety and noise sensitivity seem to have on WTN annoyance, the variable found to have the strongest association with annoyance was identifying wind turbines as the source of noise that led to window closing because it was disturbing sleep. In fact, the R^2 increased from 11% to 41% when this variable entered the final model. This is an observation that requires careful interpretation because sleep disturbance (of any kind) was not found to be related to WTN exposure in the current study

TABLE III. Multiple logistic regression model (restricted) for WTN annoyance.

Variable	Groups in variable[a]	Multiple logistic regression model ($n = 1129$, $R^2 = 0.40$,[c] H-L,[d] $p = 0.480$)		Order of entry into model: R^2 at each step
		OR(CI)[b]	p-value	
WTN (dB)[e]	Continuous	2.84 (1.96, 4.11)	<0.0001	Base: 0.11[f]
Province	ON/PEI	3.46 (1.32, 9.10)	0.012	Base: 0.11[f]
Concerned about physical safety	High/low	14.42 (7.71, 26.96)	<0.0001	Step 1: 0.28
Sensitivity to noise	High/low	5.54 (3.12, 9.84)	<0.0001	Step 2: 0.34
Personal benefit	No/yes	12.49 (1.66, 94.25)	0.014	Step 3: 0.37
Bedroom window type	Single pane	0.17 (0.04, 0.79)	0.024	Step 4: 0.38
	Double pane	0.21 (0.07, 0.63)	0.006	
	Triple pane	Reference		
Property ownership	Own/rent	5.89 (1.19, 29.06)	0.030	Step 5: 0.40
Audible road traffic	No/yes	2.08 (1.09, 3.95)	0.026	Step 6: 0.40

[a]Where a reference group is not specified it was taken to be the last group.
[b]Odds ratio (OR) and 95% confidence interval (CI) based on logistic regression model; an OR > 1 indicates that annoyance levels were higher, relative to the reference group.
[c]The Nagelkerke pseudo R^2 indicates how useful the explanatory variables are in predicting the response variable.
[d]H-L: Hosmer-Lemeshow test, $p > 0.05$ indicates a good fit.
[e]WTN level is treated as a continuous scale in the logistic regression model, giving an overall OR for each unit increase in WTN level, where a unit reflects a 5 dB WTN category.
[f]Note that the results of the base model are different from the supplemental material (see footnote 1) and Table II due to sample size differences.

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sample (Michaud *et al.*, 2016c). It is conceivable that closing the window may be an expression of the annoyance toward WTN and/or a coping strategy that protects against sleep disturbance. When closing the window reduces the indoor WTN level and hence improves sleep, this action may conceivably explain the absent association between WTN levels and sleep disturbance.

In the restricted model, variables not expected to be a direct response to wind turbine operations were considered. The rationale for such a model was that it could identify factors that may serve to diminish the annoyance response, over and above a reduction in levels of WTN exposure. The finding that concern for physical safety due to the presence of wind turbines in the area was a significant predictor of annoyance in both the unrestricted and restricted models is informative. This suggests that actions (e.g., education, community consultation) which aim to address this concern during the planning stages of a wind project may also serve to reduce community annoyance toward WTN. Noise sensitivity as a personality trait has long been known to influence the response to community noise (Job, 1988) and it is therefore not surprising that this variable was found to be associated with WTN annoyance.

In the unrestricted model, personal benefit was not retained, although this was likely due to the small number of participants in this category (i.e., 110). Indeed, in the restricted model, personal benefit was found to be statistically significant, although the increase in R^2 was rather modest (3%). Taken together with Pedersen *et al.* (2009), these findings would support initiatives that facilitate direct or indirect personal benefit among participants living within a community in close proximity to wind power projects. There was a significant effect related to window type in the current study that remained in the final model, but nevertheless appears to be counter-intuitive when considering the reduction in noise annoyance that has been reported as a result of noise insulation programs (Amundsen *et al.*, 2013; Asensio *et al.*, 2014). The odds of reporting to be highly annoyed by WTN were higher among participants who self-reported that they had triple pane windows in their bedroom. A tentative explanation for this finding could be that installing these types of windows may be a coping strategy among those who are more highly annoyed by noise. However, the potential influence this action may have on annoyance over time cannot be accounted for in the current study because no information was gathered about the time they were installed.

The possibility that elevated background noise may influence community annoyance has been reviewed by Fields (1993) with the general conclusion that the vast majority of studies reviewed indicated that ambient noise levels have no impact on community annoyance. However, wind turbines were not among the sources reviewed by Fields (1993). Certainly, there is some evidence that the association between WTN levels and annoyance is stronger in areas that are classified as quiet, compared to those classified as noisy (Bakker *et al.*, 2012; Pedersen *et al.*, 2010a,b). It has been recommended that sound levels are adjusted by up to 10 dB when estimating the prevalence of annoyance in areas where there may be a greater expectation of peace and quiet (ANSI, 1996; ISO, 2003c). In the current study, there was a tendency for BNTS levels to be slightly higher in areas where WTN levels (and therefore the prevalence of annoyance) were lower. For this reason, it is difficult to reconcile what influence, if any, BNTS had on WTN annoyance in the current study. A more appropriate assessment of the potential influence that BNTS levels may have on WTN annoyance requires a sufficient sample size in areas with similar WTN levels in the presence of varying BNTS levels. Future research in this area may clarify the influence of background noise on the overall community response to WTN, which could prove to be an important consideration in an urban planning context where it may inform decisions regarding wind turbine siting.

In the univariate analysis the odds of reporting to be highly annoyed by WTN were almost 4 times higher (95% CI: 1.17, 19.41) among participants who heard the wind turbines for 1 year or more compared to those who heard it for less than 1 year (see supplemental material[1]). Unfortunately, the limited breakdown for the audibility categories was dictated by sample size and there may be added value to having a more refined history of WTN audibility. Nevertheless, if this finding is corroborated in future research it would support sensitisation rather than habituation/adaptation with prolonged exposure to WTN.

Some discussion on the potential link between health effects and WTN annoyance is warranted. Long-term high annoyance, as a measure of community response to noise is considered to be a health effect by the World Health Organization (WHO, 1999, 2011) and has been associated with other health effects (Michaud *et al.*, 2008b; Niemann *et al.*, 2006; Pawlaczyk-Łuszczyńska, 2014; Pedersen *et al.*, 2009). This is consistent with the current findings demonstrating that participants who reported being highly annoyed by WTN were more likely to report migraines, dizziness, tinnitus, chronic pain, and restless leg syndrome (see supplemental material[1]). In addition, self-reporting to be highly sleep disturbed for any reason and rating overall quality of life as either "*very poor*" or "*poor*" were also related to WTN annoyance. Higher scores on the PSS and PSQI were likewise found to be related to WTN annoyance. Finally, hair cortisol concentrations, systolic and diastolic blood pressure were significantly higher among the participants that reported to be highly annoyed by WTN (Michaud *et al.*, 2016a). These associations between annoyance and other health effects/indicators need to be interpreted cautiously for a number of reasons. First, none of these associations were related to calculated WTN levels. Second, the R^2 in any of the reported or measured health effects was very low (i.e., $<7\%$), which demonstrates the dominance of other factors. Finally, WTN annoyance was never retained in the final multiple regression models developed for stress, sleep, or quality of life outcomes (Michaud *et al.*, 2016b; Michaud *et al.*, 2016a; Feder *et al.*, 2015). Rubin *et al.* (2014) recently reviewed studies examining symptoms related to modern technology (including wind turbines) and found that health symptoms were more commonly reported among participants who were more anxious, worried, concerned, or annoyed by a source they

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perceived to be a health risk. The authors suggested that annoyance may promote changes in physiology, behaviour, self-monitoring or enhance recall bias (Rubin *et al.*, 2014). Despite an incomplete understanding of the mechanisms through which annoyance may impact health, or vice versa, it is nevertheless relevant that there were observed associations between long-term high annoyance toward WTN and several self-reported and measured endpoints, which included elevated hair cortisol concentrations and blood pressure. Collectively, these findings support efforts aimed at mitigating community annoyance that may be associated with new wind power projects and concomitant changes in community noise levels.

V. CONCLUDING REMARKS

The complex relationship that exists between community annoyance and noise is a well-established phenomenon that has been further illustrated in the current study. This study found that the R^2 for the model with only WTN levels was merely 9% and that any efforts aimed at mitigating the community response to WTN will profit from considering other factors associated with annoyance. Although the final models had R^2's of up to 58%, their predictive strength for WTN annoyance was still rather limited. It has been shown in previous studies that trust or misfeasance with source authorities, community engagement in project development in addition to community expectations, all have an influence on community annoyance (Guski, 1999). There is also strong support for considering attitudinal factors (Job, 1988; Pawlaczyk-Łuszczyńska, 2014; Pedersen *et al.*, 2009). The relative importance of these and many other unknown factors will fluctuate across different communities. This makes it exceedingly difficult, if not impossible, to fully account for their influence on annoyance in any given community. Recently, it has been demonstrated that predicting the prevalence of annoyance to transportation noise can be much more effectively achieved using a simple one-parameter model. The analysis in the Appendix extends this methodology to WTN annoyance.

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APPENDIX: ESTIMATING COMMUNITY TOLERANCE LEVEL FOR WIND TURBINE NOISE EXPOSURE

The multiple regression models presented in the current paper demonstrate that the R^2 for the prevalence of high annoyance to wind turbine noise (WTN) exposure using a long term energy average (LAeq) alone is less than 10%. Although this increases substantially after consideration is given to several non-LAeq parameters, the predictive strength still only reaches approximately 60%. This makes it difficult to compare the prevalence of WTN annoyance to other socio-acoustic surveys and offers little confidence in estimating the prevalence of annoyance using only LAeq. Fidell *et al.* (2011) demonstrated that the wide scatter in the prevalence of aircraft noise annoyance within and between studies can be effectively accounted for with a simple model that includes only one single variable parameter, a "Community Tolerance Level" or CTL. For a detailed description of the CTL model the reader should refer to Fidell *et al.* (2011). The CTL model is based on well-accepted assumptions that in a homogenous community the prevalence of annoyance will be low or non-existent at very low sound pressure levels, and that it will increase monotonically with increasing sound pressure levels. For aircraft noise, the rate of increase in annoyance can be effectively estimated using a loudness function (i.e., sound pressure raised to the power of 0.3) and the assumption that annoyance increases monotonically with increasing sound pressure levels as shown in Eq. (A1) (Fidell *et al.*, 2011),

$$\%HA = 100\ \exp\left(-\left(1/\left[10^{(DNL-CTL+5.306)/10}\right]^{0.3}\right)\right). \tag{A1}$$

The CTL in Eq. (A1) adjusts the horizontal position of the transition function on the abscissa. The value of the CTL was obtained statistically using maximum likelihood estimation, which is a suitable approach to obtain estimates for binary data (i.e., being highly annoyed compared to not being highly annoyed). Schomer *et al.* (2012) recently demonstrated that the CTL model can also be applied to road and rail noise.

1. Calculating annual average day-night sound level (DNL) from wind turbine noise studies

Determination of CTL requires the yearly average DNL. In the current study, the yearly averaged WTN DNL was calculated at each dwelling by taking into account the effect of wind speed on the WTN sound power level (Keith *et al.*, 2016b). Wind turbine electrical power output in 10 min periods was used to derive the associated sound power. The day-night sound power level was then estimated by adding 10 dB to levels that occurred between 10 p.m. and 7 a.m. and the resulting 52 560 values were averaged over a 1 year period. At each dwelling, corrections were based on the wind park associated with the closest wind turbine. The correction applied to the sound pressure level at each dwelling was the difference between the nominal 8 m/s WTN sound power level and the yearly average day-night WTN sound power level. As described by Keith *et al.* (2016b), WTN sound pressure levels at each dwelling had been calculated for nominal 8 m/s wind speed (i.e., wind speed at 10 m height under standardised conditions according to IEC, 2012). For the few cases where operational data were not available, wind speed data were obtained from the closest wind turbines for which data were available.

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For Pedersen's studies (Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.*, 2009) the DNL was estimated by adding 4.7 dB to the 8 m/s LAeq data (van den Berg, 2008; Janssen *et al.*, 2011). Based on van den Berg (2008), DNL was assumed to be approximately equal to LDEN. In a Japanese study by Kuwano *et al.* (2014) the DNL was estimated by adding 6 dB to the measured nighttime average sound pressure level (Yano, 2015).

Not all studies in this area could be included in the current analysis because not all research designs permitted an estimate of high annoyance as a function of DNL. This was either because an equivalent to the percentage highly annoyed could not be estimated and/or the analysis of annoyance was estimated without an exposure metric that could readily be converted to DNL (e.g., distance only).

2. Applying CTL to WTN annoyance

In comparison to the large databases available for transportation noise, there are relatively few socio-acoustic surveys related to WTN annoyance. Nevertheless, the data that are currently available suggests that the loudness function in the CTL model provides an effective prediction of WTN annoyance. After converting all noise metrics to DNL, CTL can be used to quantify the differences between exposure-response relationships. By convention, the value of the CTL is the DNL from Eq. (A1) where 50% of the community would be highly annoyed. It would appear from the plots presented in Fig. 1 that the CTL model provides a reasonable fit to the available data from six field studies. It would be difficult to find a loudness function that has better

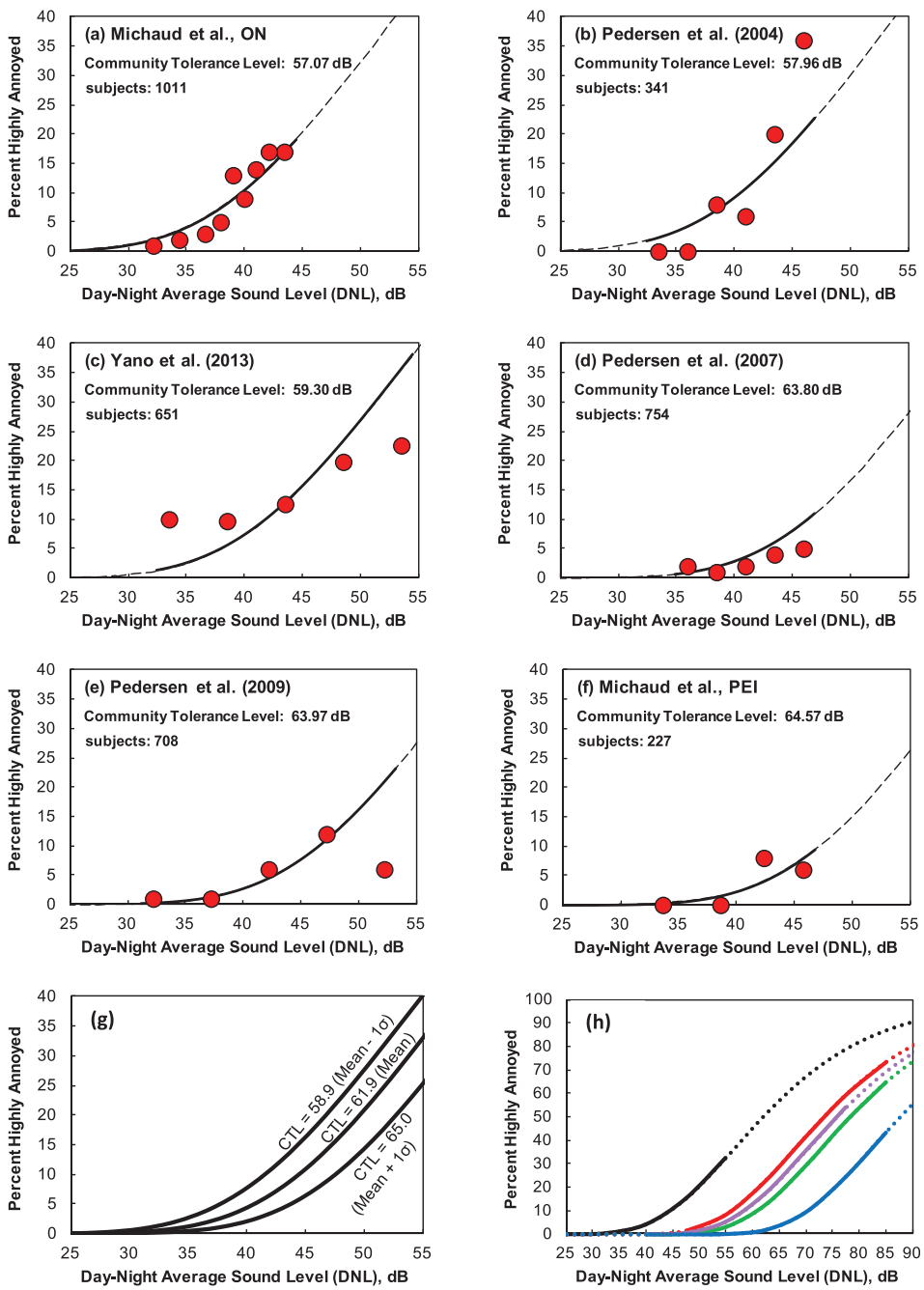

FIG. 1. Panels (a)–(f) show the best fit for the available field studies of wind turbine noise and the prevalence of high annoyance to Eq. (A1). (g) Exposure-response relationship for the prevalence of high annoyance with wind turbine noise exposure in communities of average, +1 standard deviation, and −1 standard deviation tolerance for wind turbine noise exposure. (h) Exposure-response relationship in communities with average tolerance for the prevalence of high annoyance with wind turbine noise (leftmost line, black online), aircraft noise (second line from left, red online), rail noise with high vibration (middle line, purple online), road traffic noise (right of middle line, green online), and rail noise without vibration (rightmost line, blue online).

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TABLE IV. Prevalence of high annoyance in communities with an average tolerance. CTL_{50} for WTN (61.9 dB), aircraft noise (73.3 dB), road traffic noise (78.3 dB), rail noise with vibrations (75.8 dB), and rail noise without heavy vibrations (87.8 dB).

	Noise source				
DNL	WTN	Aircraft	Road	Rail + vib.	Rail − vib.
20	0	0	0	0	0
25	0	0	0	0	0
30	0	0	0	0	0
35	1	0	0	0	0
40	4	0	0	0	0
45	11	1	0	0	0
50	21	3	1	2	0
55	33	9	3	5	0
60	45	18	9	13	1
65	57	29	18	23	4
70	67	42	29	36	9
75	76	54	42	48	19
80	82	65	54	60	30
85	87	73	65	69	43

TABLE VI. Prevalence of high annoyance in communities 1 standard deviation more tolerant. CTL_{50} for WTN (64.9 dB), aircraft noise (80.3 dB), road traffic noise (83.4 dB), rail noise with vibrations (79.3 dB), and rail noise without heavy vibrations (91.8 dB).

	Noise Source				
DNL	WTN	Aircraft	Road	Rail + vib.	Rail − vib.
20	0	0	0	0	0
25	0	0	0	0	0
30	0	0	0	0	0
35	0	0	0	0	0
40	2	0	0	0	0
45	6	0	0	0	0
50	14	0	0	0	0
55	25	2	1	2	0
60	38	6	3	7	0
65	50	14	8	15	1
70	61	24	17	26	5
75	71	37	29	38	12
80	78	49	42	50	22
85	84	61	54	62	34

agreement. The CTL for WTN ranges from 57.1 to 64.6 DNL with the grand mean of 62 and a standard deviation of 3. The calculated prevalence of WTN annoyance as a function of DNL for communities that are 1 standard deviation above and below the grand mean is provided in Tables IV–VI.

In the CNHS, the prevalence of high annoyance was nearly non-existent among the 110 participants that reported to receive personal benefit from having wind turbines in the area. This was found to have a negligible impact on CTL (∼1 dB) and for this reason they were retained in the plots shown in Fig. 1.

Quantifying WTN with an A-weighted metric has become a source of debate because wind turbines are a known source of low frequency noise (LFN) that may be undermined with an A-weighted filter. If LFN were the cause of annoyance, the loudness function would be expected to be steeper because the perception of loudness increases more rapidly once low frequencies become audible (ISO, 2003b). The only fit that would be improved with a steeper loudness function is Pedersen and Persson Waye (2004). In contrast, the data from Yano *et al.* (2013) would seem to require a shallower curve and the remaining studies can all be approximated with the same loudness function used for aircraft, road, and rail (Fidell *et al.*, 2011; Schomer *et al.*, 2012). Therefore, based on the field studies that are currently available the argument can be made that the change in high annoyance due to WTN is not driven by LFN and is effectively approximated by a long-term A-weighted metric.

TABLE V. Prevalence of high annoyance in communities 1 standard deviation less tolerant. CTL_{50} for WTN (58.9 dB), aircraft noise (66 dB), road traffic noise (73.2 dB), rail noise with vibrations (72.3 dB), and rail noise without heavy vibrations (83.8 dB).

	Noise Source				
DNL	WTN	Aircraft	Road	Rail + vib.	Rail − vib.
20	0	0	0	0	0
25	0	0	0	0	0
30	1	0	0	0	0
35	3	0	0	0	0
40	8	1	0	0	0
45	16	5	1	1	0
50	28	12	3	4	0
55	40	22	9	11	1
60	53	34	18	21	2
65	64	47	29	33	7
70	73	58	42	46	16
75	80	68	54	57	27
80	85	76	65	67	39
85	89	83	74	76	52

3. Using CTL to make source comparisons

With the CTL calculated, direct comparisons can be made to other noise sources. The corresponding overall average CTL values for aircraft, road, rail with vibration and rail without vibration are 73.3, 78.3, 75.8, and 87.8 DNL, respectively (Fidell *et al.*, 2011; Schomer *et al.*, 2012). This can be interpreted to mean that, on average, communities are about 11 dB less tolerant of WTN than of aircraft noise, 16 dB less tolerant of WTN than of road traffic noise, 14 dB less tolerant of WTN than of rail noise accompanied with high vibrations, and 26 dB less tolerant of WTN than of rail noise without vibrations. Confidence in these source differences will increase as future studies in this area produce additional estimates for the relationship between WTN levels and the prevalence of high annoyance.

4. Conclusions

The advantage of using the CTL model over multiple regression is that CTL provides a quantification in decibels for the differences between data sets that may originate from different communities and/or reflect responses to different

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noise sources. However, this approach does not identify the origins of the non-acoustic determinants of annoyance. By contrast, the multiple regression models have the advantage of identifying and quantifying non-DNL factors that are associated with individual differences in annoyance. For reflections on the advantages and disadvantages of the CTL model and multiple regressions, see Janssen and Vos (2011) and Fidell *et al*. (2011). The reality faced by jurisdictions that govern community noise policy is that they may never fully understand the myriad of reasons why communities may differ in their annoyance at comparable noise exposure levels. An assessment based on CTL side-steps the need for this type of speculation. The analysis presented here is obviously based on a limited number of field studies, and supports only preliminary conclusions. Nonetheless, further systematic collection and analysis of the relationship between WTN exposure and the prevalence of high annoyance can test and strengthen the current conclusions.

[1]See supplemental material at http://dx.doi.org/10.1121/1.4942390 for the univariate analysis results.

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