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A Critical Review of Noise Exposure Forecast (NEF) Contours and the Efficacy as a Tool for Land Use Planning

Yue Wu
University of Windsor

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A Critical Review of Noise Exposure Forecast (NEF) Contours and the Efficacy as a Tool for Land Use Planning

By

Yue Wu

A Thesis
Submitted to the Faculty of Graduate Studies through the Department of Mechanical, Automotive & Materials Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada

2020

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A Critical Review of Noise Exposure Forecast (NEF) Contours and the Efficacy as a Tool for Land Use Planning

by

Yue Wu

APPROVED BY:

______________________________________________
N. Biswas
Department of Civil and Environmental Engineering

______________________________________________
R. Gaspar
Department of Mechanical, Automotive and Materials Engineering

______________________________________________
C. Novak, Advisor
Department of Mechanical, Automotive and Materials Engineering

February 12, 2020
DECLARATION OF ORIGINALITY

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ABSTRACT

Airports provide economic and social benefits to the communities in which they are located, yet as residential development encroaches nearer to them, the noise from aircraft operations has been recognized as a contributor to increased annoyance to these residential communities. Transport Canada requires airports to publish Noise Exposure Forecast (NEF) contours to predict noise impacts on surrounding areas to help municipal planners make good land use decisions and avoid complaints.

This research examined the historical development and gives a critical analysis of the approach used to create the NEF contours. It also looks at what other counties use as planning tools. In partnership with the Greater Toronto Airports Authority, NEF contours for Toronto Pearson International Airport were compared to measured noise data and community complaints to establish a correlation.

While some good correlation was found, recommendations to improve the NEF model are given to facilitate a better land use planning tool.
ACKNOWLEDGEMENTS

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CHAPTER 1
INTRODUCTION

1.1 Airport Noise and Management

Air transport provides vital economic and significant social benefits and is essential to the world’s population. Despite all the positive effects that the presence of a busy airport contributes to the cities in which they are located, aircraft noise associated with an airport’s operations is recognized as having a primary negative impact to the residential communities which surround airports [1].

Aircraft noise from approach and takeoff operations, which is typically audible on the ground along the flight paths, can influence the daily lives of people from such effects as communication and task interference, sleep disturbance and simple enjoyment of personal time. This, along with the fact that most large airports globally are experiencing significant increases in air traffic volumes and that the development of land surrounding airports is becoming more residential, brings the issue of aircraft noise to the forefront.

To address aircraft noise impacts and the public reactions it revokes on communities around airports, the International Civil Aviation Organization (ICAO) recommended the “Balanced Approach to Aircraft Noise Management” strategy. This widely adopted approach includes four principle elements: reduction of noise at the source, noise abatement operational procedures, operating restrictions on aircraft and land use planning, [2]. These are further described in the following paragraphs.

Noise at the source is caused by the airframe and the engine of the aircraft. The design of aircraft has evolved significantly since the 1960s and has resulted in a 75%
reduction of noise at the source [2]. However, there has been no fundamental new noise control technology developed since the turbofan entered service, as aircraft are made only marginally quieter at constant weight, and have not become noisier with increasing size [1].

Noise abatement through operational procedures are in-flight and ground-based operational procedures which aimed to minimize the amount of impact and number of people affected by aircraft noise. Such procedures include, but are not limited to, using preferential runways or routes to direct the approach and departure flight paths away from noise-sensitive areas. Other flight procedures, such as gradual descent and sharp takeoff accent are designed to optimize the distribution of noise on the ground and minimize source noise are used while maintaining the required level of safety [2]. However, the safety of aircraft remains the highest priority in the development and implementation of noise abatement operational procedures.

An operating restriction is defined as “any noise-related action that limits or reduces an aircraft’s access to an airport.” It can improve the noise climate by limiting or prohibiting movements of certain aircraft types at an airport which are known to produce more noise, enabling the airport to contain or shrink the noise affected areas [2]. An operating restriction may also include the limiting of nighttime operations. These types of actions are recommended as a last resort by the ICAO.

Land use planning is a technique widely accepted for minimizing the negative impact of aircraft noise on areas adjacent to airports [3]. It requires the division of land near airports into zones according to noise conditions. Depending on the exposure level,
acceptable land uses are prescribed to each of these zones. Land use planning is especially appropriate for places where large areas of land are undeveloped and there is space to take a rational planning approach [3].

<table>
<thead>
<tr>
<th>Country</th>
<th>Prediction Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>NEF</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>NEF</td>
</tr>
<tr>
<td>Australia</td>
<td>ANEF</td>
</tr>
<tr>
<td>United States</td>
<td>DNL</td>
</tr>
<tr>
<td>Switzerland</td>
<td>NNI</td>
</tr>
<tr>
<td>Germany</td>
<td>German Störindex (Q)</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>L_{Aeq}, N_{70}</td>
</tr>
<tr>
<td>France</td>
<td>Psophique Index (lp)</td>
</tr>
<tr>
<td>Denmark</td>
<td>Lden</td>
</tr>
<tr>
<td>South Africa</td>
<td>Noisiness Index (N)</td>
</tr>
<tr>
<td>ICAO</td>
<td>WECPLN</td>
</tr>
<tr>
<td>Netherlands</td>
<td>Total Noise Load (B)</td>
</tr>
</tbody>
</table>

Figure 1: Globally Used Aircraft Noise Assessment Methods

Noise evaluation typically consists of a single number noise assessment which combines a number of factors [4]. From Figure 1, one of the most globally used cumulative noise metrics for aircraft noise assessment is the Noise Exposure Forecast (NEF).

The noise metric prescribed for use in Canada for land use planning is the noise exposure forecast (NEF) which is typically illustrated by contours with decreasing values with distance away from the airport. Below (Figure 2) is an example of a set of published NEF contours representing the modelled noise impacts for Toronto Pearson International Airport used for municipal land use planning.
Figure 2: Example of Historical NEF Contour Set for Toronto Pearson International Airport

The blue line represents the NEF 25 contour while the green and orange line represents the NEF 30 and the NEF 35 contour respectively. Transport Canada, the department within the government of Canada which is responsible for developing regulations, policies and services of transportation in Canada, mandates that adequate sound insulation for dwellings should be applied for development between the NEF 25 and 30 level as noise from aircraft exposure is likely to produce some level of annoyance [5]. It is also suggested that the zone between the NEF 30 and the NEF 35 contours, is not suitable for housing unless a detailed noise analysis is conducted and noise reduction
practices are implemented [5]. Lastly, zones above the NEF 35 contour are deemed unsuitable for housing because the number of complaints from aircraft noise are likely to be high. The NEF values and corresponding descriptions put forth by Transport Canada are outlined in Table 1.

<table>
<thead>
<tr>
<th>NEF&lt;sub&gt;can&lt;/sub&gt; Range</th>
<th>Expected Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 40</td>
<td>Repeated and vigorous individual complaints are likely. Concerted group and legal action might be expected</td>
</tr>
<tr>
<td>35-40</td>
<td>Individual complaints may be vigorous. Possible group action and appeals to authorities.</td>
</tr>
<tr>
<td>30-35</td>
<td>Sporadic and repeated individual complaints. Group action is possible.</td>
</tr>
<tr>
<td>&lt;30</td>
<td>Sporadic complaints may occur. Noise may interfere occasionally with certain activities of the resident.</td>
</tr>
</tbody>
</table>

Table 1: Transport Canada community response prediction [6]

1.2 Problem Identification and Research Objectives

As previously mentioned, the technology for noise reduction at the source is has reach a level of diminishing returns with no major scientific development expected in the coming decades. Operating restrictions are not implemented as a first resort as these can have negative operational and economic impacts on the airport. The implementation of noise abatement operational procedures offers only slight noise reductions at best; often one or two decibels. This leaves the use of strategic land use planning very important among the noise management approaches. If implemented correctly and pre-emptively, it
can offer an effective solution to aircraft noise management by eliminating the development of lands for residential use within areas that are highly impacted by aircraft noise exposure.

In a recent report by the Canadian House of Commons Standing Committee on Transportation, Infrastructure and Communities (TRAN Committee) [7], it was recommended that Transport Canada should support efforts to modernize outdated noise metrics. These efforts should include the review of Canada’s Noise Exposure Forecast model to ensure that it is in keeping with the most recent scientific evidence and international norms for noise measurement and human perception of noise.

This goal of the research included in this thesis is to conduct a review and critical analyze of the NEF system prescribed by Transport Canada which is the basis for land use planning around Canadian airports. In particular, the research focused on the following tasks:

1. Investigate how well modelled NEF contours correspond to actual noise conditions as calculated using measured noise data taken from permanent airport noise monitoring terminals (NMTs),

2. Critically analysis the validity of using the NEF 30 contour as the threshold to restrict residential development without significant noise analysis and abatement control,

3. Investigate the efficacy of the NEF system as a tool for gauging public perception and reaction to noise exposure from aircraft operations around airports.
1.3 Research Methodology

Using measured aircraft noise data at Toronto Pearson Airport, an analysis of the NEF calculation and methodology to as a land use planning tool was performed. Given the availability of historical noise data from the network of NMTs located throughout the greater Toronto area, both current and past NEF contours were evaluated. Also included in the analysis was resident complaint data collected by the airport operating authority; the Greater Toronto Airport Authorities (GTAA). Given that Toronto Pearson Airport is the busiest airport in Canada and that the greater Toronto area is also the most populous metropolitan region in Canada, an almost certain guarantee exists that enough aircraft operations noise data and representative local resident complaints data exists to carry out a meaningful analysis.

The methodology used to accomplish the research objectives, can be generally grouped as both a theoretical and numerical data analysis. The theoretical analysis includes a thorough literature review of the historical development, functions and calculation principles of the NEF metric. Other noise annoyance prediction metrics are also discussed and compared to the Canadian NEF process. The intent is to identify the hypothesized advantages and disadvantages of NEF. The data analysis involves the validation of the NEF model using measured noise data as well as an analysis of the correlation between expected community response, based on actual complaints numbers and the NEF values. The methodology used for these is as follows:
NEF model Validation:

1. Compile measured noise data ($L_{A_{eq}}$, EPNL, SEL, $L_{A_{max}}$, and aircraft event duration) from existing NMTs located near to Toronto Pearson Airport for specific dates in 2017, based on different airport operations.
2. Using the measured noise data, calculate the actual NEF values at selected NMT locations.
3. Using a global information system (GIS) mapping and information software (ArcGIS), compare the calculated NEF values to the modelled NEF contours, which are provided by the GTAA, to evaluate how close the input parameters and output values of the NEF model correspond to actual noise conditions.

Expected community response validation:

2. Plot the complaint locations on a map using ArcGIS and determine if the Transport Canada descriptions of expected community reactions to different NEF levels matches the actual complaint scenario to validate the accuracy of expected community response predictions prescribed by the NEF calculation (Transport Canada).
In summary, the plan and intended outcomes of this thesis are as follow:

• Investigate if the modelled NEF contours, which are used for land use planning, correlate to calculated NEF values determined from measured representative noise data,

• Investigate whether the NEF thresholds, as set by Transport Canada, appropriately represent the perceived level of annoyance for those exposed to aircraft noise operations,

• Compare numbers and locations of aircraft noise complaints to published and modelled NEF contours to determine if a correlation exists between the submitted community response to the predicted annoyance impacts described by the NEF thresholds.
CHAPTER 2
BACKGROUND

The intent of this chapter is to introduce and define the necessary acoustic metrics and the relevant non-acoustic principles associated with this research. It is necessary to fully understand these before a critical analysis of NEF methodology can be made.

2.1 Sound and Noise

Noise is typically defined as unwanted sound. It is acoustic energy that can be characterized by its frequency (Hz), pressure, intensity, and time-pattern [8]. The lowest and the highest frequencies of the sound audible to the average adult are approximately 20 Hz and 20000 Hz respectively [9].

The human ear is sensitive to a wide range of sound pressure. To simplify such a wide range, the sound pressure level is introduced; a logarithmic scale having the unit of decibel, often abbreviated by $dB$. A decibel is 20 times the logarithm to the base of 10 of the ratio of the measured root-mean-square (RMS) value of the sound pressure to a reference sound pressure as shown in equation 1. [10]

$$dB = 20 \log_{10} \frac{P}{P_{ref}}$$

Here $P$ is the sound pressure and $P_{ref}$ is the reference pressure level taken as the threshold of hearing for a 1000 Hz pure tone, or 20 $\mu$N/m$^2$.

2.2 A-weighted Sound Pressure Level ($L_A$)

The sensitivity of human ears varies based on different frequency bands and intensity. The human ear is not as sensitive to low and high frequencies as it is to middle
the frequencies between 500 Hz and 6 kHz, where sound is easier to be perceived at lower sound pressure levels. This makes it difficult to measure the actual perceived noise without adjusting for human sensitivity.

The A-weighting curve is an adjustment factor across the frequency spectrum, usually third octaves, that adjusts the measured sound pressure level to more closely relate to the perception of the human ear. This curve, shown in Figure 3 illustrates the attenuation or gain of the sound level at every frequency over the range of human hearing. When A-weighted, the unit of sound level is given as dBA. Figure 4 relates everyday sounds to their corresponding value in dBA.

![A-weighting curve showing the amount of attenuation or gain given to a sound level more closely relate to the perception of the human auditory system](image)

Figure 3: A-weighting curve showing the amount of attenuation or gain given to a sound level more closely relate to the perception of the human auditory system [11]
2.3 Equal-Loudness Contour

The equal-loudness contour is a measure of sound pressure level, over the frequency spectrum, for which a listener perceives a constant loudness when presented with pure steady tones. The unit of measurement for loudness levels is the Phon [13]. The A-weighting adjustment curve mentioned above is based on the 40 Phon equal-loudness contour [14]. The equal-loudness contours which were standardized in ISO 226:1987 have recently been updated in ISO 226:2003 [14]. Figure 5 illustrates both the original and updated versions of the equal-loudness contours.
Figure 5: Equal loudness level contours presented in ISO 226:1987 and ISO 226:2003 showing the relation between frequency, sound pressure level and loudness level [14]

2.4 Maximum A-weighted Sound Pressure Level ($L_{A_{\text{max}}}$)

The maximum noise level ($L_{A_{\text{max}}}$), measured in dBA is the maximum A-weighted noise level measured at an observer location during the time period in consideration [14]. Compared with an A-weighted sound pressure level for an aircraft flyover event, the $L_{A_{\text{max}}}$ represents the highest sound pressure level during the event period. However, the $L_{A_{\text{max}}}$ value provides no information to the cumulative noise exposure caused by a measured aircraft event. For instance, two aircraft flyovers having the same $L_{A_{\text{max}}}$ value may produce significantly different acoustic profiles with varying duration and average noise level; this can significantly impact the perceived acoustic experience at the ground.
2.5 Sound Exposure Level (SEL)

The sound exposure level, or SEL, is a common measurement of noise exposure for a single event, such as an aircraft flyover. The SEL is an integration of the sound pressure level over the event duration of a noise event which is then normalized to a duration of one second. The true duration is defined as the amount of time the noise event exceeds a certain noise level. Hence the SEL represents the level of energy for 1 second which contains the same amount of energy as the entire noise event as expressed in equation 2 [14]:

\[
\text{SEL} = 10 \log_{10} \int_{t_1}^{t_2} \frac{p^2(t)}{p_{\text{ref}}^2} dt
\]  

Where, \(p\) is the sound pressure, \(p_{\text{ref}}\) is the reference pressure (20 \(\mu P_a\)), \(t_1\) and \(t_2\) are the instances defining the time interval for the event.

Since SEL is normalized to one second, it will always be greater than \(L_{A_{\text{max}}}\) in magnitude. In fact, for most aircraft events, the SEL is about 7 to 12 dB higher than the \(L_{A_{\text{max}}}\) [15]. Different from \(L_{A_{\text{max}}}\), SEL is a cumulative measure meaning that a higher SEL can result from either a louder or longer event, or a combination of both.

2.6 Equivalent A-weighted Sound Pressure Level (\(L_{A_{\text{eq}}}\))

The equivalent A-weighted sound pressure level (\(L_{A_{\text{eq}}}\)) is a measure of the exposure resulting from the accumulation of A-weighted sound pressure levels over a given period of time [15]. Conceptually, \(L_{A_{\text{eq}}}\) may be thought of as the constant A-weighted sound pressure level over the period of interest that contains the same sound energy as the actual
time-varying sound level with its normal “peaks” and “dips” [15]. $L_{A_{eq}}$ is not an arithmetic value, but a logarithmic or energy-averaged value as represented in equation:

$$L_{eq} = 10 \log_{10} \left( \frac{1}{T} \sum_{i=1}^{n} (10^{0.1L_i}) \right) \quad (3)$$

where $L_i$ is A-weighted sound pressure level in dBA, T is the specified period of measurement time.

### 2.7 Day-Night Average Sound Level (DNL)

The Day-Night average sound level (DNL) is an equivalent continuous A-weighted sound pressure level over a 24-hour period that has an additional 10 dB penalty applied during the night-time (22:00-07:00) period. The penalty is intended to compensate to the period of the 24-hour day when individuals are more sensitive to noise. The equation representing the calculation for the DNL is defined by 4.

$$L_{dn} = 10 \log_{10} \left[ \left( \frac{7}{24} \right) \left( 15 \left( 10^{\frac{L_D}{10}} \right) + 9 \left( 10^{\frac{L_N+10}{10}} \right) \right) \right] \quad (4)$$

where $L_D$ is the logarithmic averaged daytime (07:00-22:00) A-weighted sound pressure level and $L_N$ is the logarithmic averaged nighttime (22:00-07:00) A-weighted sound pressure level.

### 2.8 Perceived Noise Level (PNL)

The perceived noise level (PNL) is a metric used for ranking the noisiness of sounds [14]. For aircraft noise events, it is used mainly for ranking the relative annoyance or disturbance caused by aircraft flyover noise. The noisiness can be calculated by employing the equal noisiness contours which are converted from equal loudness contours as
illustrated in Figure 6. Noisiness has the unit of Noy which is converted into perceived noise level using equation (5).

\[ PNL = 40 + 33.3 \log N \quad (5) \]

Figure 6: Graph used to relate Sound Pressure Level (SPL) to noisiness (Noy) and corresponding Perceived Noise Level (PNL) [14]

2.9 Effective Perceived Noise Level (EPNL)

The effective perceived noise level is the perceived noise level (PNL) of a single event adjusted for the effect of annoyance due to the event duration and for the presence of
discrete frequencies (tones). In the calculation, tone corrections are added first, converting the PNL into the tone corrected perceived noise level (PNLT). The calculation of tone-corrected Perceived Noise Level is detailed in the Federal Aviation Regulations, Part 36, Appendix A2 to Part 36-Section A36.4 [16]. It is generally obtained by adding a correction factor C which is added when the Perceived Noise Level has discrete frequency components (FAA 2002). The formula for PNLT, having the units TPNdB, is given as:

\[
\text{PNLT}(k) = \text{PNL}(k) + C_{\max} \quad (6)
\]

A correction factor “D” to account for the aircraft flyover duration is calculated using the following equation:

\[
D = 10 \log_{10} \left[ \sum_{k=0}^{2d} \left( 10^{\frac{\text{PNLT}(k)}{10}} \right) \right] - \text{PNLTM} - 13 \quad (7)
\]

where \(d\) is the time interval during which the level is 10 TPNdB down from PNLTM which is the maximum PNLT during the time interval and \(K\) is the index of the time step.

The effective perceived noise level (EPNL), having units of EPNdB, is calculated by adding the duration correction factor “D” as follows:

\[
\text{EPNL} = \text{PNLTM} + D \quad (8)
\]

2.10 Aircraft Noise Annoyance

Noise annoyance is defined by the U.S. Environmental Protection Agency as any negative subjective reaction to the noise on the part of an individual or group [17]. It is a complicated psychological concept, commonly measured using an ISO defined
questionnaire. Annoyance is generally recognized as the most common effect of aircraft noise on communities. It tends to increase as aircraft noise exposure increases, and with changes in noise pitch, intermittency or other acoustic characteristics [18]. Annoyance can be triggered when aircraft noise disturbs people’s lives by interfering with conversation, activities or rest. Outlined below are three mechanisms through which noise can induce annoyance.

2.10.1 Speech Interference

Speech interference can be described as the tendency of noise to “mask” speech, thus resulting in the task of having a conversation be more difficult. When the ambient noise level increases due to an aircraft event, the speaker may have to either raise his/her voice or move closer to the other person in order to maintain the conversation.

For a typical communication distances of 1 to 1.5 meters, outdoor conversations can be facilitated using a normal voice as long as the ambient noise does not exceed approximately 65 dBA [19]. This value is important as it is also the sound level that many airports, Toronto Pearson included, use to trigger the recording and data collection of a noise event by their NMTs during the daytime. Other airports often use 60 dBA during the daytime and 55 dBA during the nighttime.

2.10.2 Speech Intelligibility

The noise metric for Speech Intelligibility (SI) is described as the measure of the percentage of words transmitted and received. It can important metric to assess speech interference indoors from outdoor aircraft noise.

Different sources and regulatory organizations have recommended the maximum allowable indoor noise levels as ranging between 40 and 60 dBA $L_{Amax}$ [15]. For the
consistency of using the same outdoor noise level threshold in this thesis, and conservatively assuming an insulation attenuation of 20 dB for a dwelling with windows closed (An average well insulated wood frame home with closed windows has a noise reduction of about 26 dBA [20]), the threshold of indoor noise level of 45 dBA $L_{\text{Amax}}$ for a single event noise level to be acceptable [15]. This means that an outdoor noise level over 65 dBA may cause speech intelligibility problems. This value keeps to the consistency of the threshold for speech interference.

2.10.3 Sleep Interference

The U.S. Environmental Protection Agency identifies an indoor DNL threshold of 45 dBA during the nighttime as the necessary level to protect against sleep interference [17]. By using the same conservative assumption regarding insulation attenuation for a typical dwelling above, the corresponding outdoor DNL should not exceed 65 dBA in order to avoid sleep interference.

Sleep disruption from noise can be measured by the number of awakenings. However, sleep can be disturbed without causing awakening and the deeper the sleep, the more noise it takes to cause arousal. For the purpose of having enough noise data to cause a sleep disturbance, a 60 dBA outdoor noise level was chosen as the trigger threshold for the NMTs to record a noise event. This corresponds to an assumed indoor noise level of 40 dBA.

2.11 Aircraft Noise Complaints

Public concern about aircraft noise manifests itself in an increasing number of complaints and in growing public debate [4]. Complaints data can be an important tool to evaluate the impact caused by aircraft noise. Because of this, Transport Canada ranks
different number of complaints as criteria differentiating different zones among NEF contours. For example, Transport Canada sets the threshold that may cause noise annoyance as NEF 25. If this is the case, no complaints or very few complaints should be reported in areas below this threshold. One of the goals of this research is to investigate the validity of this.
CHAPTER 3
NEF HISTORY AND THEORIES

The Noise Exposure Forecast (NEF) is defined as a single number rating of overall noise from aircraft in the area surrounding an airport and is expressed as contour lines is 5 dB increments. It is calculated from the predicted aircraft flyover noise described in terms of the effective perceived noise level (EPNL) and the average number of flyovers per day (07:00 to 22:00) and per night (22:00 to 07:00) periods. [21]

Chapter 3 gives a detailed overview of the NEF metric including its history, calculation and supporting theory.

3.1 History of NEF

There are five steps in the development of the NEF. The first four are the evolution of the Composite Noise Rating (CNR), which is the predecessor of the NEF. The following sections, outline the evolution of each of these steps, tracing the changes from one to the next as well as the justifications given for these changes.

3.1.1 First Version of Composite Noise Rating

CNR was first proposed by Rosenblith and Stevens in 1952 [22]. At this stage, the term “effective stimulus” was applied to describe the physically measurable and other identifiable characteristics. These characteristics are associated with the noise source and the community environment which might affect the response of a community to the noise [21]. Items that may affect the result of CNR are listed as: [21]

1. A measure of the average noise level spectrum in octave frequency band for the noise source
2. The presence or absence of discrete frequency components.

3. The impulsive or non-impulsive nature of the sounds.

4. Repetition of the sound.

5. Background noise level in the community.

6. The time of day during which the noise source operates.

7. An adjustment for adaptation of the community through previous exposure to the noise.

The noise level is calculated by the average sound pressure level in octave frequency bands. The band spectrum level is overlaid against a series of curves termed “level rank” curves (Fig 6) which approximate a set of equal loudness curves separated in 5 dB intervals. The level rank into which the highest octave band SPL protruded is selected as the primary descriptor of the magnitude of noise level in the CNR calculation [21]. This procedure eventually evolved into the perceived noise level (PNL) which was applied in the later version of the CNR.

The presence or absence of discrete frequencies is also considered in this version of the CNR calculation procedure. It is defined that when any audible frequency components are present, the “effective stimulus” is essentially 5 dB higher than if the discrete frequencies were not present [21]. This procedure was abandoned in later versions of CNR but was adopted again in the last version of CNR.

“Impulse” is another intuitive correction factor that was introduced. It was suggested that if any impulsive characteristics were associated with the noise source, the effective stimulus is increased by 5 dB over the steady state noise level of the source [21].
The repetition of the source, which is now known as the “duration effect” of the noise, was also considered. It was introduced by providing a table which gave correction numbers related to the number of times during the day that the individual source was present [21].

The community background noise was taken into consideration by separating it into categories denoted as “very quiet”, “suburban”, “residential urban”, “urban near some industry”, and “area of heavy industry” with corresponding corrections to the effective stimulus varying between +5 to −15, with +5 for the very quiet and −15, for the loud heavy industrial areas [21].

The time of day factor is for whether the event is during the day and night, or whether it was present only during the daytime. In this version of CNR a reduction of 5 dB to the effective stimulus was applied if the operations only happened during the daytime [21].

The last factor relates to the adaptation of a given community to the noise. Value of -5 dB and -10 dB may be applied in accordance with how well the community is able to adapt to the repeated events. No correction is applied if the noise event is new.

Items 1 through 4 are physical characteristics of the noise source itself, while the rest are correlated to other attributes that are situational factors. Considering all the listed factors, the result is arranged into a six-element scale of response:

1. No annoyance
2. Mild annoyance
3. Mild complaints
4. Strong complaints
5. Threats of legal action
6. Vigorous legal action

In this version of CNR, the 5 decibels interval, when evaluating the effective stimulus, gives rise to the calculation result being discontinuous given it is based on the experience that a change of noise level of less than 5dB does not produce a significant change of reaction to the noise. This makes the calculation more based on the experience than on measured results.

3.1.2 Second Version of CNR

A modified form of the previous CNR was published by Stevens, Rosenblith, and Bolt in January 1955 [23]. The adjustments to the calculation related factors are described as follows:

- The correction due to background noise level was expanded to a range of +10 to -15 decibels.
- The repetitiveness of the noise source was revised to become the percentage of time the source operated in an 8-hour period.
- The adjustment for summertime and wintertime operation or wintertime only was added. In this case, a reduction of −5 dB was applied in the effective noise stimulus calculation when the noise source operated during the wintertime only.

The other modification involved the description of the community responses. The scale was modified from a 6-element scale to a 5-element scale as follows [23]:

1. No observed reaction
2. Sporadic complaints
3. Widespread complaints
4. Threats of community reaction
5. Vigorous community reaction
This modified CNR procedure formed the basis for a proposed International Standards Organization (ISO) rating system for community response to noises of all types [23]. However, when predicting community response to a specified noise source, the expected level of community response may still be less or more than predicted by this procedure, because again, the input is largely based on people’s experience and not from a scientific basis.

3.1.3 Third Version of CNR

For the purpose of evaluating noise levels and planning land use around air bases, the U.S. Air Force started to develop a new approach in the late 1950’s to rate aircraft noise exclusively. The 1957 publication by Stevens and Pietrasanta [24] was a significant step in developing this approach. It was the first attempt to modify the CNR metric as an aircraft noise effect prediction method.

The major change from the previous study was the simplification in describing the physical nature of the noise sources. While the original level ranking curves were still used in deriving the sound magnitudes in this procedure, the simplification was applied by using only the sound pressure level in the 300 to 600 Hz band instead of all eight octave bands as used previously. The was to give focus to the problematic noise frequencies generated by aircraft. Further, corrections related to the discrete frequencies and impulsiveness were eliminated in this version. It was not because these two factors were no longer important, but because they were not present in most military turbojets noise of that time [24].

The repetitiveness correction was also improved. It became a strict energy summation which was calculated by \(10 \log_{10} \frac{\delta t}{3600}\) [21] where \(\delta t\) here is the effective
duration of the signal. This correction was added to the simplified “level ranked” noise level.

The background noise correction remained similar to what was used in the earlier version but now with a modified range from +5 dB for very quiet suburban to a −10 dB correction for a noisy urban community.

Some adjustments to the penalty for time-of-day were also applied. Daytime was described as 06:00 to 18:00, evening, from 18:00 to 23:00, and nighttime, from 23:00 to 06:00. It was defined that daytime only operations were given a −5 dB correction and nighttime operations a +5 dB correction. No correction was necessary for evening time.

New corrections concerning community attitudes and public relations around air bases were included. A correction of −5 dB was applied for two situations. The first one is when a community has some previous exposure to noise from air base operations, but little effort was made to foster good public relations. The other one is when a community has not been exposed to noise from air base operation previously, but some effort has been made to foster good public relations. Here, −10 dB is added when a community has considerable previous exposure to noise from air base operations and a −15 dB correction is applied when a community has a good relationship with the air base [24].

The equivalent sound pressure level (not $L_{eq}$) which represented the “effective stimulus” value can be expressed as: [21]

\[
\text{Equivalent SPL} = L_{\text{max}} + 10 \log_{10} \frac{\delta t}{3600} + \text{other corrections}
\]  

(9)

where the $L_{\text{max}}$ is the maximum SPL in the 300 to 600 Hz band.
The scale for community response was once again reduced from 5 to 3 levels. Given in Table 2 is a description of the community response and the corresponding Equivalent SPL [21]:

<table>
<thead>
<tr>
<th>Description of Community Response</th>
<th>Equivalent Continuous SPL in 300-600 Hz Octave, Plus Corrections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Essentially no complaints are reported: the noise may, however, interfere occasionally with activities of the residents</td>
<td>Less than 45 dB</td>
</tr>
<tr>
<td>Some residents in the community may complain, perhaps vigorously. Concerted group action is probably not brought against the authorities, but the possibility of such action exists.</td>
<td>45 to 55 dB</td>
</tr>
<tr>
<td>Concerted group action is brought against the authorities. The community action may vary from strong threats to vigorous action.</td>
<td>Greater than 55 dB</td>
</tr>
</tbody>
</table>

Table 2: Community response and Equivalent SPL

3.1.4 Fourth Version of CNR

A draft of the document “Land Use Planning with Respect to Aircraft Noise” was completed in 1963 [25]. The old level ranking system was eliminated while a new noise level calculation method called Perceived Noise Level (see section 2.8) was adopted. The
repetitiveness, or the total duration of noise over a given time period was considered by applying a correction factor for the number of aircraft operations which can be described as \(10 \log N\) where \(N\) is the number of operations. To simplify the calculation, only two time-of-day periods were considered; day from 07:00-22:00, and night from 22:00-07:00. In this version, the time correction factor required nighttime noise exposure to be 10 dB less than daytime exposure [21]. The background noise level correction was also dropped from the adjustments in this version. Similarly, the adjustment for previous exposure and public relation no longer existed. The community response scale stayed almost the same, which were essentially no complaints, some complaints, and vigorous complaints.

When considering only the daytime operation, the CNR calculation can be expressed as: [20]

\[
\text{CNR} = PNL_{\text{max}} + 10 \log N - 12 \tag{10}
\]

where \(PNL_{\text{max}}\) is the maximum perceived noise level and \(N\) is the numbers of aircraft operations. After relating this to the previous equivalent SPL value and the corresponding community response, the upper and bottom levels of CNR are 127 dB and 112 dB respectively. This translates to the equivalent SPL values of 55 dB and 45 dB respectively. To obtain values that are multiples of 5, these values were normalized by subtracting 12 dB from each [20]. The CNR threshold number and corresponding expected community response is shown in Table 3:
<table>
<thead>
<tr>
<th>Composite Noise Rating (CNR)</th>
<th>Description of Expected Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 100</td>
<td>Essentially no complaints would be expected. The noise may, however, interfere occasionally with certain activities of the resident.</td>
</tr>
<tr>
<td>100 to 115</td>
<td>Individuals may complain, perhaps vigorously. Concerted group action is possible</td>
</tr>
<tr>
<td>Greater than 115</td>
<td>Individual reactions would likely include repeated, vigorous complaints. Concerted group action might be expected.</td>
</tr>
</tbody>
</table>

Table 3: CNR value and corresponding community response

### 3.1.5 Inception of NEF

In the late 1960s, the Noise Exposure Forecast (NEF) model emerged as a consequence of the continued evolution of the PNL concept [21].

This time, the perceived noise level was replaced by the effective perceived noise level (EPNL see section 2.9) which included both the discrete frequencies and duration factors in one metric. One-third octave sound pressure levels were used instead of one octave data. Computations were required for each one-half second of the flyover time pattern in order to determine the discrete tone and duration corrections [21]. This made the calculation of the EPNL a much more complicated procedure than PNL.
The adjustments to EPNL values to obtain the “effective stimulus” were the same as those used on the 4th version of CNR [21]. In order to distinguish the NEF metric and CNR metric, a numerical factor is subtracted from the summation of EPNL.

No new information on community response was applied to these studies. The range of different responses in the CNR development was retained intact based on Galloway and Von Gierke’s research [26]. The identification of numerical values for NEF to be used in describing the zonal separations was performed by mapping the NEF values for a series of operations against the CNR values computed for the same set of operations[21]. Then the community response boundary levels were determined as an equivalence of NEF 40 to CNR 115 and NEF 30 to CNR 100.

3.2 NEF in Canada

The CNR system was initially used by Transport Canada as a tool for land use planning around airports and then it was replaced with the NEF model. [27]. There was no obvious change initially when the NEF was applied in Canada. The only difference was the expansion of the expected community response description between NEF 30 and NEF 40 [20] (See Table 1).

3.3 NEF Calculation Principles

In order to have a better understanding of NEF model and its function, the NEF calculation and the principles it follows are introduced in the following sections.

3.3.1 NEF Formula

The NEF calculation formula is defined as follows and is summed over all aircraft types and all flight paths [20]:
\[
\text{NEF} = \langle \text{EPNL} \rangle + 10 \cdot \log(N_d + 16.7 \cdot N_n) - 88 \quad (11)
\]

where EPNL is the energy mean value of the and \(N_d\) and \(N_n\) are the number of flights during the day (0700 to 2200) and night (2200 to 0700) respectively. The factor 16.7 represents a 10-to-1 weighting of night flights [28]. The constant number 88 is an arbitrary number.

### 3.3.2 Equal Energy Principle

The most common basic hypothesis concerning the combination of noise levels and number of noise events is that annoyance is proportional to the total energy of the aircraft noise events [20]. Many noise annoyance models including the NEF calculation follow this principle and are of a form that looks close to the following [20]:

\[
\text{Noise Annoyance} \propto \langle \text{SEL} \rangle + K \cdot \log(N) \quad (12)
\]

where \(\langle \text{SEL} \rangle\) is the integrated sound exposure level for an average aircraft and \(N\) is the total number of such events.

To determine the best \(K\) value to give a weighting to the number of events, Rice [29], Rylander et al.[30] and Fields [31] presented research about the trade-off between levels and numbers of events. Their results suggested that a \(K\) value equal to 10 would yield the most balanced approach. If \(K\) is exactly 10, then the summation, \(\langle \text{SEL} \rangle+10\cdot\log(N)\), corresponds to the total energy of the aircraft noise events[20]. The NEF uses \(K=10\). There are other values of \(K\) that have been used for the evaluation of aircraft noise annoyance (Example: In the Noise and Number Index (NNI) \(K=15\), in the German Störindex (Q) \(K=13.3\)). They will be discussed in the next chapter. When the \(K\)
value is greater than 10, the calculation gives more emphasis on rather than the noise level of aircraft.

3.3.3 Frequency Weighting

As mentioned in Chapter 2, the NEF uses the EPNL to physically evaluate the aircraft noise level. It considers the different sensitivity of the human ear for different frequencies, the presence of pure tones and the duration of each aircraft noise event.

The frequency weighting applied to the EPNL is the PNL which was based on equal noisiness contours. It is like the equal loudness contours. The equal loudness and equal noisiness contours are not parallel but tend to converge at lower frequencies which more correctly approximates the response of the hearing system. The contours also represent the pattern of changing frequency response of the hearing system with changing sound level [20].

3.3.4 Time Weighting

It has been generally accepted that noise during the evening and nighttime hours cause more disturbance and annoyance than during the daytime.

As mentioned in the NEF history, initially a 5dB night-time weighting was used. This was changed to a 10dB night-time weighting in the NEF. This means that the integrated noise exposure over the nine hours of night-time period should be 10 dB greater than the integrated noise exposure over the fifteen hours of day-time period. As a result, assuming the same number of flight operations per hour during the 9-hour-night-time period as the 15-hour-day-time period, the night-time operation number are multiplied by
10(15/9) which is 16.7. This adds a correction of +12.2 dB to the NEF calculation, \((10 \log_{10} 16.7 = 12.2)\).

### 3.3.5 Flight Type, Number, and Mix of aircraft

The NEF value can be calculated based on current flight information such as flight types, number of movements, runway use etc. Alternatively, for long term predictions (more than 10 years in advance) the Noise Exposure Prediction (NEP) can be calculated based on the predicted flight information. For future aircraft noise annoyance level prediction, it is the priority to predict the aircraft operation details; the total number of aircraft operations, the number of operations for each aircraft type, the portion of the operations that are during the night-time hours, the stage length of each departing flight, the runway use, and the flight paths to be followed [20].

Transport Canada recommends that NEF values be calculated based on the number of operations occurring on a Peak Planning Day (PPD) which is approximately a 95th percentile day [6]. The number of operations for a PPD is estimated by using the number of operations for the seven busiest days of the three busiest months [20]. By such estimation, the number of operations for a PPD is determined and used to predict the number of operations in the future.

### 3.4 NEF Computing System

Contours of equal NEF values in the vicinity of an airport are generated using NEFCalc, a Transport Canada computer software program. The shape and extent of these contours depend upon the types of aircraft, the flight paths, their altitude and the number of operations performed by each aircraft type [32]. Once the aircraft operations data is obtained, it is inputted into the NEFCalc software which computes the NEF values at
predetermined locations in the form of a rectangular grid array. The extent of the grid and the spacing between the grid points is prescribed by the user.

3.4.1 Aircraft Data

Noise and takeoff data for most aircraft are contained in the data base within NEFCalc (some special aircraft noise data must be inserted by user). The noise data is in the form of tables of EPNL values in decibels versus slant perpendicular distance (SPD) for each aircraft type [32]. The slant perpendicular distance is the shortest distance between a ground location and an aircraft’s flight path.

The noise table for each aircraft type consists of four relationships between EPNL and SPD: one for takeoff thrust with the aircraft well above the ground as seen by an observer (takeoff), a second for landing thrust, another for takeoff thrust with the aircraft close to the ground (sideline case), and a fourth for noise abatement takeoff at reduced thrust (overhead) [32]. When the aircraft flight path is determined, NEFCalc uses the appropriate relationship between EPNL and SPD to calculate the NEF value at a specific location.

3.4.2 Flight Path

The flight path is another important input parameter for NEFCalc. It can be divided into departure and approach flight paths.

The departure flight path is first defined by specifying the runway and whether the departure flight path is straight out, curved, or a circuit. For curved departures or circuits, the turning or circuit directions, the angles of the turns, the heights and/or distances from brake release at which the turns are initiated and the turning rates must all be specified [32].
Since there may be several different departure routes from a single runway, several flight paths may be specified for the same runway.

The specification of the approach flight path is limited to the variation of altitude with distance from the runway threshold since NEFCalc assumes a straight-line approach to the runway [32]. Since the approach to a given runway may be the same for many aircraft types, there are normally fewer approach flight paths than departure flight paths.

3.4.3 NEF Contour Plotting

As mentioned before, the output of NEFCalc is in the form of NEF values at prespecified grid locations. This means the user must define the rectangular grid system before running the simulation. Any convenient point may be chosen as the origin of the coordinate system. Usually the end of one runway is selected [32]. So long as the grid is defined, the calculation of the NEF values at each grid point can be processed based on the input data mentioned previously.

The calculated NEF value at each grid point is based on a relatively large number of a logarithmic summing procedures. This makes the largest (or loudest) event weight more heavily than the smaller (or quieter) events. The final NEF contours result from connecting grid points which have the same NEF values and smoothing the contour lines as was illustrated in Figure 2 in the first chapter.
CHAPTER 4
CRITICAL ANALYSIS OF NEF

The discussion given in chapter 3 detailed to principles and general approach for the NEF calculation procedure. These theories were defined in the last century with some based on scientific calculation while some were based on experience, assumption or simple observation, yet the approach is still being used 50 to 70 years later. This chapter gives a critical analysis of the NEF calculation, particularly as a land use planning tool.

4.1 Outdated community survey

As stated in Chapter 3, the Transport Canada suggested descriptions of expected community response for given NEF values remain mostly the same as in the last version of the CNR which were developed over 50 years ago. These descriptions were based on general impressions of community response for a small number of specific case studies. The research from this study has found that they were not subsequently at any time changed or improved to reflect the results of more modern systematic community surveys of residents near airports and they have not been influenced by studies on any Canadian subjects [20]. Thus, no serious attempt has been made to validate the scale of NEF values and their corresponding descriptions of expected community response. With many technological and social changes over the last 40 years, it is likely that the outdated survey data is not applicable to current conditions.

From the Transport Canada’s NEF scale (Table 1), complaints data is seen as a critical tool for gauging community’s response to aircraft noise. Unfortunately, complaints data often does not correlate well with noise levels [20]. Complaints have been shown to be influenced by the socio-economic status of complainers and their general ability to be
an effective complainer [20]. An overdependence on complaints data may lead to difficulty in establishing a rational land use plan. This becomes a significant shortcoming of the current NEF system and may cause error when used for aircraft noise annoyance prediction.

When assessing the effects of aircraft noise on communities, it is important to examine the level of annoyance experienced at different levels of noise exposure. This is best done through an annoyance survey using standardized ISO survey questions and scales. The results of such surveys can be used to undertake any necessary adjustments to the current NEF scale. A future task of the larger research project for which this thesis is included is to create and execute this type of survey in the vicinity of Toronto Pearson Airport.

4.2 Shortcoming of Equal Energy Principle

As discussed previously, the equal energy principle generally consists of the following components: Noise Annoyance $\propto <\text{SEL}> + K \cdot \log(N)$. The NEF calculation follows this rule with $K=10$ which makes this equation a total energy summation. Transport Canada suggests that any area with a NEF value above 25 will result in some level of annoyance. Setting NEF 25 as a constant value in the NEF equation will allow for the simple comparison between the number of events and corresponding EPNL values.

Assuming only daytime operations are considered, the NEF equation can be expressed as $\text{NEF} = \text{EPNL} + 10 \cdot \log(Nd) - 88$. With a constant NEF value of 25 and for the flight number is set to be 1, 10 and 100, the relationship between the event number and EPNL values is shown in Figure 7. It is demonstrated that a value of NEF 25 can be the result of one loud aircraft operation with an EPNL of 113 EPNdB or 100 operations of
quieter aircraft with an EPNL of 93 EPNdB. The NEF system implies that both situations should evoke the same or similar community response, however intuitively it can be hypothesized that 100 aircraft events will likely cause higher levels of annoyance. As such, a shortcoming of application of the equal energy principle is that the same energy level will not necessarily represent the same acoustic experience or annoyance level, but will also be dependent on such things as the number of events, time of day, etc.

Figure 7: Equivalent Operations for NEF 25 for Varying EPNL Representing Differing Aircraft Event Numbers

4.3 Shortcomings of EPNL

The Noise Exposure Forecast uses the EPNL metric as a quantitative noise level evaluation method. Although the EPNL calculation includes a frequency weighting,
adjustment for pure tones, and duration correction, there is still a lack of evidence of EPNL as the most accurate predictor of community responses to the aircraft noise.

As mentioned in Chapter 2, the first step in the EPNL calculation procedure is to convert the measured noise to PNL using a special frequency weighting method using the equal noisiness contours. Next, pure tone and duration corrections are added. This three-step procedure makes the EPNL calculation complicated and time-consuming compared to other more simplified noise metrics, such as variation of Ldn and Leq which other countries have tested to have similar or better predictive attributes, when related to annoyance.

Another example of a simple method is the A-weighting method. The A-weighted sound pressure level and the Perceived Noise Level of aircraft were found to be related to each other with a standard deviation of only 1.6 dB [33]. The difference between PNL and dBA are commonly found to be 12 dB for jet aircraft [34]. For the rating of noise levels in areas near airports, the difference of accuracy between A-weighted level and Perceived Noise Level is less than 0.5 dB and only about 0.3 dB for tone corrected PNL values[20].

As mentioned above, the EPNL considers the event duration. Sound Exposure Level (SEL) is an alternative, simpler noise metric that also considering the duration of the noise. It is the integration of the A-weighted sound pressure level over the duration of a noise event and normalized to a referenced duration of one second, as was described in chapter 2. Figure 8 lists a small selection taken from over 4000 events at Toronto Pearson with their corresponding SEL and EPNL values. The standard deviation between EPNL and SEL is about 1.2 dB and the average difference between these two metrics is 1.2 dB as well.
Neither the 1.6 dB standard deviation between the A-weighted sound pressure level and PNL nor the 1.2 dB standard deviation between the EPNL and SEL is within the audible range of difference in level for the human auditory system. This means that all the complicated procedures applied when generating the EPNL do not have a noticeable improvement in the aircraft annoyance prediction. Given this, a simpler frequency weighting like A-weighting, and a noise exposure metric like SEL might be a better choice.

### 4.4 No rigorous Time Weighting

As described in Chapter 3, no daytime weighting exists and a 10 dB night-time weighting is used in the NEF by multiplying 16.7 by the nighttime operation number. This number is not supported by extensive scientific evidence but is rather a consensus of various “common sense” type arguments from groups responsible for the development of the various noise measures [20]. For example, one could argue that lower noise levels are
expected during night-time because sleep is easier to be disturbed by nighttime operation noise than most day-time activities. However, there may also be an argument that an evening time weighting should be included given that people are trying to enjoy their time personal relaxation and family time and aircraft noise would interfere with this expectation. It is beyond the scope of this study to validate the correction factors for daytime, evening time, or night-time weighting procedures; however, this is a consequential weighting that should be verified through jury testing and / or annoyance surveys.

4.5 Inaccurate prediction of future operations and PPD

For future aircraft noise level prediction, it is vital to have the ability to accurately predict aircraft operations details such as flight type, number, mix of aircraft. Errors in each of these input variables will influence the resulting NEF values and therefore the contour areas. Expected errors in NEF values and contour areas for various changes in the input data (based on the assessment from three Canadian airports) is shown in Table 4. Here, it is seen that the change of input data relating to operations and PPD estimation caused the highest error. As a worst case scenario, up to 2 dB of error in average NEF values and up to 30% in contour areas is possible [20].

<table>
<thead>
<tr>
<th>Input Data Change</th>
<th>Change in Mean NEF, dB</th>
<th>Change in Contour Area, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>±20% total operations</td>
<td>±1 dB</td>
<td>±10 to 15%</td>
</tr>
<tr>
<td>±40% total operations</td>
<td>±1.5 dB</td>
<td>±13 to 26%</td>
</tr>
<tr>
<td>±10% in PPD estimate</td>
<td>0.4 dB</td>
<td>±4 to 7%</td>
</tr>
<tr>
<td>+20% night operations</td>
<td>0.3 to 0.5 dB</td>
<td>+4 to +7%</td>
</tr>
<tr>
<td>Input Data Change</td>
<td>Change in Mean NEF, dB</td>
<td>Change in Contour Area, %</td>
</tr>
<tr>
<td>--------------------------</td>
<td>------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>+1 stage length</td>
<td>-0.3 to 0 dB</td>
<td>±4%</td>
</tr>
<tr>
<td>+20% aircraft</td>
<td>-0.3 to 0 dB</td>
<td>-4 to +2%</td>
</tr>
<tr>
<td>+20 use of one runway</td>
<td>-0.1 to +0.5 dB</td>
<td>-3 to +9%</td>
</tr>
</tbody>
</table>

Table 4: Summary of expected errors in NEF values and contour areas for various changes in input data [20]

4.6 Analysis of NEF compared to other metrics

Different countries have chosen to adopt different type of noise metrics to measure and depict the magnitude and effects of aircraft noise on communities. Besides the NEF system, other widely used aircraft noise effect prediction methods around world are introduced in this section. Comparisons are given between these methods and the NEF approach used in Canada.

4.6.1 Australia Noise Exposure Forecast (ANEF)

Australia uses a modified version of the NEF metric referred to as the ANEF to describe the aircraft noise impact around aerodromes [35]. It is the same as the original NEF measure used in Canada except for different time-of-day weightings. There is no daytime weighting and the evening starts from 19:00 to 22:00 hours followed by the night-time, from 22:00 to 7:00 hours. Both evening and night noise have a 6 dB penalty (calculated by $10\log_{10} 4 = 6$) [33]. The formula is given as follows: [36]

$$\text{ANEF} = \text{EPNL} + 10 \log_{10}(N_D + 4N_E + 4N_N) - 88$$

(13)

where EPNL is the energy-averaged effective perceived noise level, the $N_D$, $N_E$, and $N_N$ are day, evening, and night-time separately.
The ANEF measure is the result of a large survey of residents near major Australian airports. The survey concluded that people were more disturbed by aircraft during the evening period and that a reduced night-time weighting was acceptable [3].

4.6.2 Day-night Level ($L_{dn}$)

The Day-Night Level $L_{dn}$ is used in the United States to characterize environmental noise including aircraft noise. As described in Chapter 2, it is an integrated energy equivalent A-weighted measure ($L_A$) with a 10 dBA night-time weighting. The night-time period is from 22:00 to 7:00 hours. The $L_{dn}$ is defined as [1]:

$$L_{dn} = 10 \log_{10} \left[ \frac{1}{24} \left( 15 \left( 10^{\frac{L_D}{10}} \right) + 9 \left( 10^{\frac{L_N+10}{10}} \right) \right) \right]$$

(14)

If the time weighting is not considered, then $L_{dn}$ would be equal to $L_{Aeq}$ for 24 hours.

4.6.3 Day Evening Night Level ($L_{den}$)

Denmark uses the $L_{den}$ metric which is an integrated energy equivalent A-weighted level like $L_{dn}$, but with an additional 5 dB evening penalty between 19:00 and 22:00. Thus, the time weighting was expanded to 0 penalty for the daytime from 07:00 to 19:00, 5 dB penalty for evening time from 19:00 to 22:00, and 10 dB penalty for nighttime from 22:00 to 07:00. The $L_{den}$ is defined as [36]:

$$L_{den} = 10 \log_{10} \frac{1}{24} \left( 12 \times 10^{\frac{L_{day}}{10}} + 4 \times 10^{\frac{L_{evening}+5}{10}} + 8 \times 10^{\frac{L_{night}+10}{10}} \right)$$

(15)

Where $L_{day}$ is day time equivalent A-weighted sound pressure level, $L_{evening}$ is evening time equivalent A-weighted sound pressure level, and $L_{night}$ is night time.
equivalent A-weighted sound pressure level. The $L_{den}$ noise metric is now broadly used by the European Union, Japan, and Vietnam [36].

### 4.6.4 Noise and Number Index (NNI) and $L_{Aeq}$

The original NNI was developed by the United Kingdom as a method for assessing noise exposure and community response. It can be expressed by the following equation [21]:

\[
\text{NNI} = \overline{PNL_{max}} + 15 \log_{10} N - 80 \tag{16}
\]

where $\overline{PNL_{max}}$ is the average maximum noise level in PNdB for the aircraft flyovers and $N$ is the number of aircraft in a certain time period.

The NNI was derived from a study in which physical aircraft noise measurements were taken at 85 locations within 10 miles of London (Heathrow) Airport. Approximately 2000 people living in the same area were then interviewed concerning their general satisfaction or dissatisfaction with their living environment [21]. Based on this, two physical variables were found to affect the aircraft impact on communities. One is the average maximum noise level in PNdB and the other is the number of flights which could be heard. The PNdB calculation was determined by physical measurements which covered 100 successive flyovers at each location with the purpose of defining the statistical distribution of level and time. It was estimated that doubling the number of events is equal to a 4.5 PNdB increase in noise level. Thus, the impact factor relating to number of flights was represented as $15 \log_{10} N$ in the NNI. The constant of 80 was developed by assuming the annoyance scale was zero when the noise level was 80 PNdB. The NNI was then replaced by equivalent continuous sound level $L_{Aeq}$ which has no time penalties but is
calculated for day hours and night hours separately. The daytime is defined as 07:00-23:00 while the night-time is defined as 23:00-07:00. The 16-hour day time $L_{Aeq}$ equation is defined as [36]:

$$L_{Aeq,16hr} = (SEL)avg + 10 \log_{10} N_{16hr} - 47.604 \quad (17)$$

where $(SEL)avg$ is the average sound exposure level, and $N_{16hr}$ is the number of flights during the 16-hour daytime.

**4.6.5 Total Noise Load (B)**

The Total Noise Load (B) was developed by the Netherlands to assess aircraft noise impact. It is specified by the following equation [21]:

$$B = 20 \log_{10} \sum N 10^{L_A/10} - 157 \quad (18)$$

Here $L_A$ is the Maximum A-weighted sound pressure level for aircraft flyovers and $N$ is the number of aircraft movements in the 24 hour period.

The development of B was based on interviews of 1000 respondents located in eight communities surrounding the Schinphol Airport, Amsterdam [21]. The Maximum A-weighted sound pressure level was applied in the calculation to account for the aircraft noise physical characteristics. The effect of the number of events is presented in an energy summation basis way as $20 \log_{10} N$.

**4.6.6 Mean Annoyance Level, $\overline{Q}$**

Mean Annoyance Level represented as $\overline{Q}$ is an aircraft noise annoyance assessment method developed and used in Germany.
\[
\bar{Q} = 13.3 \log_{10}\left\{ \frac{1}{T} \sum_{k} 10^{L_A} \cdot \tau_k \right\}
\]

(19)

where \(L_A\) is the A-weighted sound pressure level in dBA, \(\tau\) is corresponding aircraft event duration and \(T\) is the period of time.

\(\bar{Q}\) is calculated by firstly summing different noise levels multiplied by corresponding duration and then averaging over a specified time and multiplying a constant. If the constant is 10, the process will be an energy average of noise levels. However, instead of simply using an energy average, the constant 13.3 was used in Germany which corresponds to 4 dB increase of noise exposure per doubling the duration [21].

Since \(\bar{Q}\) considered the duration of noise for every event, it is not directly comparable to CNR or NEF unless a certain time pattern \(T\) is decided. If \(T\) is defined as \(8.64 \times 10^4\) seconds which equals to 24 hours, and assuming the average single event duration is 10 seconds, \(\bar{Q}\) can also be represented as:

\[
\bar{Q} = L_A + 13.3 \log N - 52.3
\]

(20)

4.6.7 Weighted Noise Exposure Level, WECPNL

WECPNL was developed by the International Civil Aviation Organization (ICAO) and is currently used by Korea, China and Nigeria. It is an energy average of the effective perceived noise levels from overflights at different times of day and night. The formula is described as follows [36]:

\[
\text{WECPNL} = \text{EPNL} + 10 \log_{10}(N_1 + 3N_2 + 10N_3) - 39.4
\]

(21)
where EPNL is the energy average of the effective perceived noise levels; \( N_1 \) is the number of operations during day time 07:00-19:00, \( N_2 \) is the number of operations during evening time 19:00-22:00 and \( N_3 \) is the number of operations during night time 22:00-07:00.

4.6.8 Isopsophic Index (I)

The Isopsophic Index, symbolized by I, was initiated by the French Ministry of Transport and is defined as [21]:

\[
I = \overline{PNL_{\text{max}}} + 10 \log_{10} N - 30 \tag{22}
\]

where \( \overline{PNL_{\text{max}}} \) is the average maximum noise level in PNdB and \( N \) is the number of aircraft in a certain time period.

This index I is calculated from the Mean \( \overline{PNL_{\text{max}}} \) and the number of events based on an energy summation. Assuming that each aircraft movement causes a disturbing noise for 30 seconds and aircraft movements occur at a maximum rate of one per minute, and considering daytime hours only from 06:00 to 22:00, this results in a maximum of 960 movements per day [21]. Because \( 10 \log 960 \approx 30 \), the constant number “30” is approximated.

4.6.9 Comparisons and Analysis

Given in Table 5 is a summary of the discussed aircraft noise annoyance evaluation metrics. When compared to the NEF metric, it is evident that almost all the metrics, other than the \( L_{dn} \), and \( L_{den} \) metrics, use the same equal energy principle. The ANEF and WECPNL both use the EPNL, as does the NEF. The most used metric, however, remains the A-weighted sound pressure level which is at least a component of the determination of
the $L_{dn}, L_{den}, B,$ and $\bar{Q}$ metrics. Alternatively, the NNI and I index use the PNL metric and the $L_{Aeq}$ metric uses the calculation of SEL to calculate noise level.

The time-of-day penalties are quite different amongst the metrics. NEF has the largest night penalty among all the mentioned metrics. However, the NEF does not include an evening time weighting such as ANEF’s 6 dB penalty, WECPNL’s 5 dB penalty, and $L_{den}$ 5 dB penalty for evening noise. It is suggested that further research into the NEF may consider adding an evening time penalty.

Most of these metrics use an expression like $10 \log N$ to describe the equal-energy-based noise effect caused by several aircraft. Some examples are $B\ (20 \log N), \bar{Q}\ (13.3 \log N),$ and NNI $\ (15 \log N)$ which place higher emphasis on the number of events. As mentioned previously, when the value for $K$ value in equation (12) is over 10, it is given that the number of flights is assumed to have a more negative effect to annoyance than the noise level itself. As aircraft continually get quieter, but increase in volume, it is critical to study and compare the impacts of number of events versus noise level. It may be relevant that the outcome from such a study could be incorporated into a revised NEF metric.

It is also worth mentioning that among all these metrics, only NNI used the actual measured aircraft noise data across many different sites as the input information for the modeling of noise impact. The NEFCalc. uses manufacturer supplied aircraft noise data which is embedded in the software. Here, no input parameters from measured ground noise levels are included. The validation of the NEF computer model using measured data, while understandably burdensome, is critical and constitutes one of the key objectives of this research as given in the next chapter.
<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Noise Level Evaluation</th>
<th>Time-of-day Penalties</th>
<th>Countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEF</td>
<td>(\text{NEF} = \text{EPNL} + 10 \log (\text{Nd} + 16.7 \text{Nn}) - 88)</td>
<td>EPNL</td>
<td>12.2 dB nighttime</td>
<td>Canada, China (HK)</td>
</tr>
<tr>
<td>ANEF</td>
<td>(\text{ANEF} = \text{EPNL} + 10 \log_{10} (\text{N}_0 + 4 \text{N}_E + 4 \text{N}_N) - 88)</td>
<td>EPNL</td>
<td>6 dB evening and nighttime</td>
<td>Australia</td>
</tr>
<tr>
<td>WECPNL</td>
<td>(\text{WECPNL} = \text{EPNL} + 10 \log_{10} (\text{N}_1 + 3 \text{N}_E + 10 \text{N}_N) - 39.4)</td>
<td>EPNL</td>
<td>5 dB evening and nighttime</td>
<td>Korea, China, Nigeria</td>
</tr>
<tr>
<td>(L_{dn})</td>
<td>(L_{dn} = 10 \log_{10} \left[ \frac{1}{24} \left( 15 \left( \frac{L_A}{10} \right) + 9 \left( \frac{L_N}{10} \right) \right) \right] )</td>
<td>(L_A)</td>
<td>10 dB nighttime</td>
<td>US, Brazil</td>
</tr>
<tr>
<td>(L_{den})</td>
<td>(L_{den} = 10 \log_{10} \left( \frac{1}{24} \left( 12 \cdot 10 \frac{L_A}{10} + 4 \cdot 10 \frac{L_N}{10} + 8 \cdot 10 \frac{L_N}{10} \right) \right) )</td>
<td>(L_A)</td>
<td>5 dB evening and nighttime</td>
<td>(European Union), Japan, Vietnam</td>
</tr>
<tr>
<td>(B)</td>
<td>(B = 20 \log_{10} \frac{L_A}{10} + 20 \log_{10} N - 157)</td>
<td>(L_A)</td>
<td>no</td>
<td>Netherlands</td>
</tr>
<tr>
<td>(Q)</td>
<td>(Q = L_A + 13.3 \log N - 52.3)</td>
<td>(L_A)</td>
<td>no</td>
<td>Germany</td>
</tr>
<tr>
<td>(L_{Aeq})</td>
<td>(L_{Aeq,16hr} = \text{SEL}<em>{avg} + 10 \log</em>{10} N_{16hr} - 47.604)</td>
<td>SEL</td>
<td>no</td>
<td>UK</td>
</tr>
<tr>
<td>NNI</td>
<td>(\text{NNI} = PNL_{max} + 15 \log_{10} N - 80)</td>
<td>PNL</td>
<td>no</td>
<td>UK (before)</td>
</tr>
<tr>
<td>(I)</td>
<td>(I = PNL_{max} + 10 \log_{10} N - 30)</td>
<td>PNL</td>
<td>no</td>
<td>France</td>
</tr>
</tbody>
</table>

Table 5: Summary of Aircraft Noise Annoyance Evaluation Metrics
CHAPTER 5
EXPERIMENT OF NEF VALIDATION

As mentioned previously, this research is a collaboration between the University of Windsor and Toronto Pearson International Airport. This chapter details the methodology used to validate of the NEF contours which have been calculated to represent the noise impacts from the flight operations at this airport. This was approach in two ways as follows:

1. Compare the modelled NEF contours to calculated NEF values based on real noise data measured during the year 2017 using permanently installed noise monitoring terminals (NMTs).

2. Compare the Transport Canada community reaction descriptions associate with the different NEF thresholds to actual community complaint data collected by the airport authority.

5.1 NEF Contours & NMTs Locations

The airport authority (GTAA) generated a set of 2017 NEF contours using the traffic volumes for the busiest air traffic day in 2017 (August 18th) instead of the Peak Planning Day (PPD) as prescribed by Transport Canada. This was to generate contours that represent the worst air traffic scenario. However, following the normal NEF calculation procedure, the type of operations, routing structure, runway configuration, and aircraft weight were defined as on an annual average-daily-basis [37]. This means all the input data for the representative 2017 NEF contours corresponds to the average values for all inputs, except traffic volume, for the whole year (2017). For example, the runway usage input is an average of how frequent each runway was used for 2017. Figure 9 illustrates the 2017
NEF contours which was generated by the GTAA with all the described inputs and plotted in ArcGIS.

Shown in Figure 10 is the present locations for the airport’s NMT installations with respect to the 2017 NEF Contours which were produced by the GTAA. In order to validate
the results from the NEF model, historical noise data for the same time period that the NEF contours represent was compiled from the NMTs located closest to the contours.

5.2 Validation of NEF Model

As discussed in chapter 4, errors in the NEF model can be caused by inaccurate predictions to the number of airport operations, runway use and flight paths or by inaccuracies in the aircraft sound power data provided by aircraft manufactures; data which itself is modelling and not derived by actual in-flight measurements.

The process of calculating the NEF contours based on measured noise data would be laborious and would require the installation and maintenance of far too many NMT’s to

Figure 10: Location of Present NMT Installations with the 2017 NEF Contours produced by ArcGIS
be feasible. Because of this, the NEF contours must be created by the airport authorities using predictive modelling.

5.2.1 Data Collection

The noise monitors around Toronto Pearson International Airport are programed to trigger and start recording noise data when the measured noise level exceeds 65 dBA during the daytime and 60 dBA during the nighttime. These types of acoustic conditions are referred to as “events.” The EPNL data for a noise event over 65 dBA is calculated by the noise meter for every trigger. The collected data shows when these events occur as well as their durations and EPNL values. As part of this, the triggering of an event is correlated to real time radar information to verify the presence of an aircraft. This is to ensure that no erroneous noise data from other environmental sources (e.g. lawnmower) is recorded and used for any calculations of aircraft noise reporting.

Figure 11 is an example of EPNL data collected for NMT site Number 1, accompanied with the duration, time of occurrence, and recording threshold. The NMT ID is the serial number of the NMT, the unit of duration is seconds, the unit of threshold is dBA, and the unit for EPNL is $EPNdB$.

<table>
<thead>
<tr>
<th>RMTID</th>
<th>STARTDATE</th>
<th>ENDDATE</th>
<th>DURATION</th>
<th>THRESHOLD</th>
<th>EPNL</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>18/08/2017 00:07:42</td>
<td>18/08/2017 00:07:55</td>
<td>14</td>
<td>60</td>
<td>71.5</td>
</tr>
<tr>
<td>7</td>
<td>18/08/2017 14:03:35</td>
<td>18/08/2017 14:03:39</td>
<td>5</td>
<td>65</td>
<td>80.8</td>
</tr>
<tr>
<td>7</td>
<td>18/08/2017 14:06:12</td>
<td>18/08/2017 14:06:16</td>
<td>5</td>
<td>65</td>
<td>83.4</td>
</tr>
<tr>
<td>7</td>
<td>18/08/2017 14:17:06</td>
<td>18/08/2017 14:17:10</td>
<td>5</td>
<td>65</td>
<td>82.5</td>
</tr>
<tr>
<td>7</td>
<td>18/08/2017 19:04:03</td>
<td>18/08/2017 19:04:12</td>
<td>10</td>
<td>65</td>
<td>76.4</td>
</tr>
</tbody>
</table>

Figure 11: Example Report of Data Collected by an Airport NMT
5.2.2 Data Filtering

In order to further validate the noise data collected by the NMT’s as an aircraft flyover along and not contaminated by other sources of noise, the data was put through a filtering procedure prior to using it for the NEF calculation. This filtering was performed using additional data from Highchart output which is a second by second timeline of noise data which coordinates the radar data to noise data from the monitors. Figure 12 is an example of the Highchart for a single event.

![Highchart Example](image)

Figure 12: Example of a Highchart Event Recorded by an NMT Showing the Presence of an Aircraft Flyover

Given the presence of an overflight above or near the noise monitoring terminal, the illustrated red line will verify the presence of an aircraft along with the other relevant information including flight operation number, flight code, and distance from the NMT.
The blue line represents the ambient noise level. The time information will appear as well when the cursor points to a certain spot on the chart. The illustration shown in Figure 12 is also an example of perfect recorded event as indicated by the yellow shaded stripe that depicts the duration of the recording. A perfect event happens when the peak sound pressure level matches the shortest distance of the aircraft from the monitor.

As part of the filtering process, all perfect events were retained in the collected data and included in the calculation of the NEF value for the location. Imperfect events such as the one shown in Figure 13 were excluded from the calculation of the NEF. The described filtering procedure was done for every NMT during the 24-hour period that the NEF contours traffic data was based on. This was to ensure a proper correlation between the modelled NEF contours and the calculated values based on the measured noise data.

Figure 13: Typical Examples of NMT Data during the Filtering Process to Ensure Data Quality
5.2.3 Calculation Procedure

After the removal of non-aircraft event data, the remaining data was used to calculate the NEF value at the NMT locations. The 24-hour NEF calculation process began by calculating the equivalent EPNL value following the energy-averaged calculation methodology as expressed with the following equation:

\[
EPNL_{eq} = 10 \cdot \log_{10} \left( \frac{t_1 \cdot 10^{EPNL_1} + t_2 \cdot 10^{EPNL_2} + \cdots + t_n \cdot 10^{EPNL_n}}{t_1 + t_2 + \cdots + t_n} \right)
\]  \hspace{1cm} (23)

where \( EPNL_{eq} \) is the equivalent \( EPNL \), \( t_n \) is the duration of each recorded noise event and \( EPNL_n \) is the \( EPNL \) value for every recorded noise event.

The 24-hour equivalent \( EPNL \) was calculated by inputting every corresponding filtered event data in the 24 hours into the equation.

The NEF value for events that occurred during the day can be calculated with calculated 24-hour EPNL data. The number of recorded events during daytime \( (N_D) \) and during the night-time \( (N_N) \) were also inserted in the NEF equation. With such information, the 24-hour NEF value for a given site can be calculated as:

\[
NEF_{24} = EPNL_{24} + 10 \log_{10} (N_D + 16.7 \times N_N) - 88 \]  \hspace{1cm} (24)

where \( NEF_{24} \) is the 24-hour period NEF value, \( EPNL_{24} \) is the equivalent 24-hour \( EPNL \) value, \( N_D \) is the numbers of events during the daytime, and \( N_N \) is the numbers of events during the nighttime.

Figure 14 shows the 24 hours of recorded events at NMT site number 7 measured on August 18th in 2017.
Figure 14: The Noise Data Measured at NMT07 on August 18th, 2017

The NEF calculation shown below details the steps of the process:

a. Calculating the 24-hour equivalent $EPNL$:

$$EPNL_{24} = 10 \log_{10} \frac{14 \cdot 10^{-10} + 5 \cdot 10^{-10} + 80.8 \cdot 10^{-10} + 83.4 \cdot 10^{-10} + 82.5 \cdot 10^{-10}}{14 + 5 + 5 + 10} = 79.17$$  \hspace{1cm} (25)

b. Counting the number of daytime events ($N_D$) and the number of nighttime events ($N_N$) in the 24-hour period.

c. The third step is calculating the 24-hour NEF value:

$$NEF_{24} = EPNL_{24} + 10 \log_{10} (N_D + 16.7 \times N_N) - 88$$

$$= 79.16 + 10 \log_{10} (4 + 16.7 \times 1) - 88$$

$$= 4.32$$  \hspace{1cm} (26)

NEF values for other sites with high traffic volumes can also be calculated in the same way as shown above.

5.2.4 Validation of the Modelled NEF Contours (East-West Runway Operation)

In order to validate the modelled NEF contours, the NEF values for the NMT locations were calculated for August 18th, 2017, as detailed above. While the contours

<table>
<thead>
<tr>
<th>RMTID</th>
<th>STARTDATE</th>
<th>ENDDATE</th>
<th>DURATION</th>
<th>THRESHOLD</th>
<th>EPNL</th>
<th>Total Numbers of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>18/08/2017 00:07:42</td>
<td>18/08/2017 00:07:55</td>
<td>14</td>
<td>60</td>
<td>71.5</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
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<td>18/08/2017 14:03:39</td>
<td>5</td>
<td>65</td>
<td>80.8</td>
<td>Number of night events</td>
</tr>
<tr>
<td>7</td>
<td>18/08/2017 14:06:12</td>
<td>18/08/2017 14:06:16</td>
<td>5</td>
<td>65</td>
<td>83.4</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>18/08/2017 14:17:06</td>
<td>18/08/2017 14:17:10</td>
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<td>82.5</td>
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</tr>
<tr>
<td>7</td>
<td>18/08/2017 19:04:03</td>
<td>18/08/2017 19:04:12</td>
<td>10</td>
<td>65</td>
<td>76.4</td>
<td>4</td>
</tr>
</tbody>
</table>

Number of day events

4
represent the NEF for the busiest traffic day of 2017, it is important to note that the traffic was predominantly directed in the East-West direction due to the wind direction on the given day. This leaves scenarios with heavy North-South traffic, under-represented, as will be discussed in next section. The resulting NEF values for each NMT site are shown in Figure 15.

<table>
<thead>
<tr>
<th>NMT ID</th>
<th>#1</th>
<th>#2</th>
<th>#4</th>
<th>#5</th>
<th>#7</th>
<th>#9</th>
<th>#11</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEF</td>
<td>30.15</td>
<td>25.69</td>
<td>21.78</td>
<td>13</td>
<td>4.33</td>
<td>28.02</td>
<td>11.19</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>NMT ID</th>
<th>#12</th>
<th>#13</th>
<th>#14</th>
<th>#18</th>
<th>#20</th>
<th>#21</th>
<th>#22</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEF</td>
<td>-12.4</td>
<td>17.74</td>
<td>8.83</td>
<td>23.54</td>
<td>24.96</td>
<td>16.85</td>
<td>9.6</td>
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<table>
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<th>NMT ID</th>
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<th>#30</th>
<th>#31</th>
<th>#32</th>
<th>#33</th>
<th>#34</th>
<th>#35</th>
</tr>
</thead>
</table>

Figure 15: Calculated NEF Results using Measured Noise Data from each NMT Location on August 18th, 2017

In order to compare the calculated NEF values to the modelled NEF contours, the calculated NEF values were plotted on a map along with the contours as illustrated in Figure 16.

Noted in Figure 16, the calculated NEF values for site #1 and #9 (highlighted in red) are higher than expected based on the NEF model. Two sites lie either close to the upper east or west end of the NEF 25 contour. Arguably, the calculated NEF values for sites 4, 18, 20 and 34 are also higher than expected, albeit still lower than the next contour threshold. Inversely, the NEF values at site #5, #11, #12, #14 and #27 (highlighted in green) are smaller than expected which implies an uneven traffic distribution amongst the runways on this specific date. This is clearly the case upon examination of the flight tracks shown in Figure 17.
In order to accurately represent the most severe noise exposure scenario in all cardinal directions, the same NEF calculation process was performed for another date which had the heaviest North-South traffic day for 2017 as discussed in the next section.

Figure 16: Comparison between Calculated NEF values and Modelled NEF Contours
5.2.5 NEF Modelled Contours Validation (North-South Runway Operation)

The busiest north-south air traffic day in 2017 was April 7th. The same calculation process as with the East-West NEF validation was performed for this 24-hr period.

Instead of 21 NMT sites, only 17 sites were established on this specific day as the other four NMTs were not yet installed. Given in Figure 18 are the calculated NEF values with site numbers.
The comparison of the modelled NEF contours and calculated values are given in Figure 19. All sites with calculated NEF value exceeding the modelled contours are highlighted in red.

![Comparison of Calculated NEF Values and the Modelled NEF Contours for April 7th, 2017](image)

For this traffic scenario, the calculated NEF values exceeded the modelled contours at many locations. Part of the reason why this is that this type of traffic flow is highly...
unusual and may not be considered in the modelling of a “typical” traffic distribution. Nonetheless, it has occurred in the past, and some consideration is due. The heavy north-south traffic flow distribution explains most the exceeded NEF values in Figure 19 apart from sites #18 and #20 which lie closer to the end of the east and west runways. To understand the reason for the higher than expected NEF values at these two sites, analysis of the flight paths was performed as shown in Figure 20.

Figure 20: Flight paths on April 7th, 2017 with NMT locations

Figure 20 is the combination of flight paths with NMT locations and NEF contours. The yellow lines represent the arrival flights and the green lines represent the departures. Both sites #18 and #20 are highlighted in red. On this day, only the north and south runways were used. As such, the excess of aircraft noise at sites #18 and #20 was not caused by east
and west runway air traffic. From the flight tracks, many aircraft arriving from the west or north west were flying over site #18 and #20 as they were lining up to land. This flight pattern explains the overload of these two specific sites close to the west end of NEF 25 contour.

This portion of the NEF validation process demonstrated that communities around site #4, #5, #7, #11, #12, #13, #14, #18, #20, #22 and #27 were exposed to higher than expected aircraft noise when the north-south runways were predominantly used. This in turn may result in some unexpected and severe reactions from individuals living near to these flight paths.

5.3 Validation of NEF Description of Expected Community Reactions

As stated previously, the NEF contours prescribed in Canada attempt to define degrees of annoyance / public reaction and correlate these to the various NEF exposure levels (see Table 1). For NEF values between 35 and 40, an “individual complaints may be vigorous”; For NEF values between 30 and 35 “sporadic and repeated individual complaints are possible”; For NEF values lower than 30 “Sporadic complaints may occur” [5]. If such descriptions were correct and the NEF contours were modelled correctly, then it is assumed that most complaint locations should fall within the NEF 25 contour with few sporadic instances outside or near this threshold contour.

To test this hypothesis, aircraft noise complaints data for 2017 was compiled. Complaints were divided based on their severity levels. The “severity” means how often a single complainant submits multiple complaints. The “low” severity level is when a complainant submits between 1 to 5 complaints per year, “slight” as 6-12 complaints,
“mild” as 13-52 complaints, “moderate” as 53-156 complaints, “severe” as 157-365 complaints, and “extreme” as 366 complaints or more. The results are given in Table 6.

<table>
<thead>
<tr>
<th>Severity Level</th>
<th>Low</th>
<th>Slight</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount</td>
<td>1700</td>
<td>225</td>
<td>179</td>
<td>57</td>
<td>28</td>
<td>25</td>
</tr>
<tr>
<td>Percentage of total</td>
<td>76.78%</td>
<td>10.16%</td>
<td>8.08%</td>
<td>2.57%</td>
<td>1.26%</td>
<td>1.13%</td>
</tr>
</tbody>
</table>

Table 6: Severity of complaints in 2017

A low severity level represented the majority of complaining, thus it was decided to use unique complaints data (despite how many times one address complained, only one complaint was counted) to most accurately represent most of the community reaction. Shown in Figure 21 is the 2017 complaint locations in relation to the 2017 NEF contours.
Most complaint locations fall outside the NEF 25 contour. Only 9.11% of the unique complaint locations fall within the NEF 25 contour.

The areas of highest complaint concentration in 2017 are located around sites #4, #5, and #7 which were shown to be significantly underestimated by the NEF model, particularly on the date with heavy north-south traffic volumes. This may explain why these high complaints volume areas are outside of the NEF 25 contour. Complaints locations outside of NEF 25 contour and around locations #11, #12, #13, #27, #18, #20 and #22 can also be explained by the higher than expected aircraft noise levels due to the busy north-south runways operations. This far in the analysis, if the NEF model would
encompass the higher calculated NEF values, the expected community reactions (complaint location clusters) might correspond well with the proposed NEF thresholds for annoyance. Even if the NEF contours were expanded to more appropriately represent areas of high noise exposure, there are still several locations around the airport (site #32, #33, #34, #35, #36 and #37) that exhibit high number of complaints. As seen in Figure 15, the calculated NEF values for these locations are not particularly high and cannot reasonably explain noise-induced annoyance. This result is discussed in the next chapter.

5.4 Limitation of Experiment

The complex nature of aircraft noise, its measurement, evaluation and prediction, in addition to the subjective nature of community reaction to this stimulus, grants a certain level of error and limitation to this experiment. Some of the limitations of the undertaken research are discussed below.

5.4.1 NEF Contours Limitation

In this experiment, the 2017 NEF contours were generated based on the busiest air traffic day in 2017 instead of the 95th percentile day as stipulated by Transport Canada. The limitation could be the result of a larger contour than that found using air traffic volume on PPD.

Using the PPD for the input parameters, means that NEF values would be averaged over 21 days using the energy-averaging calculation, which may camouflage severe scenarios like the example of the heavy north-south operations. Thus, using the busiest day’s traffic volume seems more representative because it appears to correlate better to the complaint locations.
5.4.2 Limitation Caused by Data Collection

NMTs only record events and provide EPNL values when noise level reaches 65 dBA during the day 60 dBA during the night. This can lead to some aircraft events not being represented or accounted for in the NEF calculation. This in turn can affect the NEF calculation result due to lower number of aircraft movements during the daytime and nighttime. However, without low noise level events, the equivalent effective perceived noise level will get increased resulting in higher NEF calculation results as well. This trade-off situation makes it difficult to predict if the final NEF calculation will be increased or decreased by these two effects. Lowering the event threshold would eliminate this restriction on the data, allowing for more inclusion of aircraft noise events. However, this may introduce additional difficulties relating to filtering through non-aircraft events and interference of background noise with measurements. This issue is still being debated and further research is necessary to establish what would result in the most accurate outcomes.

5.4.3 Limitation Caused by Data Filtering

Due to file size, recorded audio files of noise events are not kept indefinitely, making it difficult to conclude with absolute certainty if an event is aircraft triggered, especially when the Highchart data does not align perfectly. This situation requires a judgement call which in turn may skew the NEF calculation to some extent.

5.4.4 Limitation Caused by NMT Establishment

The experiment outlined above relies on the establishment of the NMT network around Toronto Pearson Airport. In 2017, this network was still under construction. On both April 7th and August 18th, data from some critical sites was not available, making the
NEF validation impossible for those areas. For example, the validation calculation could not be performed due to lack of data from site #36, #37, #38 and #39 on August 18th.

As seen from the calculated NEF values, even the NMT locations near one another can exhibit very different NEF values making it difficult to generalize about the noise conditions of an extended area based on calculations at one given point. In order to accurately describe / calculate the noise conditions of an entire region affected by aircraft noise, the NMT locations would have to be located much closer to each other; something which is financially unfeasible. Considering the physical and financial restrictions, the NMT network GTAA has is enough as the monitor locations are chosen based on their proximity to flight paths, proximity to noise-sensitive land use, background noise level, utility source, site access and security and so on.

5.4.5 Limitation Caused by Existing Land Use Planning

The existing zoning around the airport prescribe few residential developments inside the NEF 30 contour. Many more densely populated residential zones fall outside the NEF 30 and NEF 25 contour, which can be hypothesized to be one of the reasons why more complaints come from outside these contours. Should that be the case, these results still warrant a revision of the Transport Canada description of expected community reactions outside the NEF 30 or 25 contour.
6.1 Research Findings

The experimental results show that on August 18th, 2017, the busiest east-west air traffic day, most calculated NEF values do not exceed what has been simulated by the NEF model, except sites #1 and #9. This is expected, as the NEFCalc software allocates the input departure and arrival numbers to each runway based on the annual average percentage of runway usage (predominantly east-west runway at Pearson airport).

The experiment results on April 7th in 2017, are very different. Calculated NEF values for sites #4, #5, #7, #11, #12, #13, #14, #18, #20, #22 and #27 all significantly exceed the modelled NEF contours. 11 sites out of 19 showed considerable deviation from the NEF noise model. This discrepancy was most evident in sites #5, #7, #12, #13 and #14 which lie outside the NEF 25 contour and showed calculated NEF values over 30. This can be explained by the way how the NEF model allocates the numbers of aircraft for each runway. The weather conditions and wind direction in Toronto, usually result in predominantly east-west runway usage. As such, when the simulation uses the annual-average-basis methodology to allocate numbers of aircrafts for each runway, the effects of north-south runways traffic will be underestimated.

In general, the NEF contours simulated by software works much better for the east and west runways direction than for the north and south runways direction. The modelled NEF contours do not even closely resemble the measured noise exposure conditions with heavy north-south runway usage. The deviation between the model and calculated values can be fixed by adjusting the input parameters to represent the worst-case scenario for each
runway independently. It is highly recommended that the airport should consider worst air traffic cases in order to ensure effective long-term land use planning.

Canada’s overreliance on NEF contours for land use planning can also be considered as a potential issue. If residential zoning is permitted in areas with potential high noise exposure (even if this noise exposure is intermittent) individuals will be annoyed and express this annoyance in complaints or legal action. Therefore, it is essential to account for irregular traffic distribution in the NEF models, showing worst case scenarios.

From the map showing the 2017 unique complaints locations (Figure 21), the most concentrated complaint areas are located around NMT sites #4, #5 and #7. On April 7th, the NEF values for these three sites are 28.89, 33.5 and 31.41 respectively. This may explain the concentration of complaints in these areas. Individuals in these areas were exposed to a lot more aircraft noise than one might accept. In several areas where the NEF value was calculated between 30 and 35, the expected community response was validated by complaint data (Transport Canada - “individual complaints may be vigorous”). The northern complaint areas around site #11, #12 and #22 can also be explained by higher than expected aircraft noise exposure (Figure 19).

Upon examination of the April 7th NEF values, the results for the southerly located sites #4, #5 and #7 are similar to the calculated values for sites #11, #12, #13, #14 and #22 (Figure 19). However, examination of the map showing the concentration of complaints (Figure 21) shows that there are many more complaints in the vicinity of sites #4 #5 and #7 than to the north. Examination of the flight paths on this day (Figure 20) show a high concentration of flights over these areas. However, for August 18th, site #7 has the highest
concentration of flights (Figure 17) amongst all the NMT locations. The interesting point is that the flights are still at a high elevation at these locations, thus the low calculated NEF values, but yet high concentrations of complaints. This is assumed to be best explained by alternative non-acoustic factors, such as the visual impacts from the aircraft. It is these factors that can contribute greatly to annoyance and complaints yet have low NEF values. It is recommended that non-acoustic factors be considered in any future developments of the NEF calculation when trying to improve the NEF model.

Other complaint areas around the airport are sporadic which generally match the Transport Canada prescribed description of community reactions in areas outside the NEF 30 contour.

Nonetheless, there were still concentrations of complaints that occurred far from the airport. Complaints around NMT sites #32, #33 and #34 are examples where the calculated NEF values (Figure 15) were not high even on the busiest traffic days (site #33, the NEF value was 12.77 on the busiest traffic day).

One possible explanation for these clusters of complaints may be the airspace changes that took place in 2012, which introduced relatively low levels of aircraft noise to previously unaffected communities.

Based on the results of this experiment it can be hypothesized that unexpected complaint clusters including areas around site #4, #5, #7 and #33, could be the result of excessive noise exposure to unexpected aircraft operations. However, further research is necessary to affirm this statement, for example looking at complaint locations on the dates used in the calculations.
Unexpected community reactions around site #4, #5 and #7 may be explained by the failure of the NEF model to predict unusual circumstances / operations. Additional research could be done to explain problems around site #33. Other non-acoustic factors may also be considered when analyzing areas of high complaint volumes but low NEF values. For example, housing prices neighborhood characteristics and socio-demographics of population may have an impact on complaint volumes and distribution. Further investigations to this are presently being carried out by others.

6.2 Summary

- The performance of the modelled NEF contours and NEF thresholds, and consequently the efficacy of the NEFs as a tool for land use planning, appear to relate to actual noise exposure conditions for the case of typical runway distribution.
- In contrast, special circumstances such as unusual runway usage and traffic distribution is almost completely unaccounted for by the NEF model.
- The result is that land use planning decisions based on the NEF contours can result in residential development encroaching on regions where people can experience greater disturbance resulting in higher incidence of annoyance.
- The Transport Canada descriptions of expected community reactions to different NEF exposure levels are found to be at times understated. And are most applicable in areas nearest to the airport where the NEF values are highest.
CHAPTER 7
RECOMMENDATIONS FOR FUTURE WORK

Based on the state of the art and the NEF validation discussed in this thesis, the following chapter contains recommendations for possible improvements of the NEF model and overall noise annoyance prediction. Improvements to the NEF metric and model are necessary in order to make it a more suitable tool for noise annoyance prediction. This will in turn optimize the land use planning process, and better inform other noise annoyance mitigation strategies.

The first recommendation relates to the qualitative descriptors of expected community reactions at various NEF levels. Transport Canada should update these severely outdated descriptors to reflect current social conditions and increased noise sensitivity amongst the population. This should be done through large scale surveys across aircraft noise affected communities. In doing so, more accurate community response indicators can be developed. These would be an improvement over the current indicators of expected number of complaints or the propensity for legal action. In addition, this exercise will update the dose-response relationship and help revise existing noise thresholds. Outcomes from advanced surveys could provide a better understanding of the shortcomings identified in this research associated with the equal energy principle.

In recent years there have been improvements in the science of psychoacoustics, including a better understanding of the fundamental mechanisms behind loudness. However, little work has been done on improving or updating the frequency weighted metric for aircraft noise (EPNL). Jury testing of responses to frequency ranges associated
with aircraft noise could better evaluate sound quality aspects that contribute to annoyance. Updating this metric, will impact NEF values and models as this is the main variable in the NEF equation.

Another recommendation for future research would be to examine if the NEF contours relate well to complaints as well as annoyance. In this research it was found that there are areas within the community around the airport that have high concentrations of complaints that do not correlate well with NEF contours. Complaints and annoyance are often incorrectly used interchangeably. By executing a community annoyance survey, locations of highly annoyed responses can be plotted on a map and compared to complaint clusters. Further research is needed to first establish locations of high annoyance, and secondly relate these to noise exposure. If a clear correlation does not exist, further examination of non-acoustic contributors needs to be undertaken.
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VITA AUCTORIS

NAME: Yue Wu

PLACE OF BIRTH: Nanjing, Jiangsu, China

YEAR OF BIRTH: 1991

EDUCATION: Nanjing University of Information Science & Technology, Nanjing, Jiangsu, China, 2013

University of Windsor, M.Eng., Windsor, ON, 2016

University of Windsor, M.Sc., Windsor, ON, 2020