

# Fuzzy Modeling of Annoyance Caused by Aircraft Noise Using $L_{aeq_d}$ and $L_{aeq_n}$ Metrics

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**ABSTRACT:** Airport noise presents a major environmental impact arising from aircrafts airport activities, being one of the most complex and difficult mitigation problems. From the environmental point of view, airports cause serious problems to the population. Annoyance caused by noise was evaluated from the Day-Night Level (*DNL*) metrics proposed by Schultz. However, acoustic comfort is assessed separately during the day and at night, because the noise adverse effects are different. In this context, this paper presents a study on sound impact assessment related to noise annoyance caused by aircraft and aims to establish a method to analyze the sound impact on inhabited communities that are in the vicinity of airports. Besides, it proposes reviews available in literature and discusses noise annoyance exposure caused by transportation systems in an evolutive context. The study was based on criteria of evaluation levels planned for comfort of the community according to the Brazilian Standard ABNT/NBR 10151. Therefore, a fuzzy logic system was developed in order to establish a relationship between the percentage of people highly annoyed by adverse noise effects around the airport, Day Equivalent Sound Level ( $L_{Aeq_d}$ ) and Night Equivalent Sound Level ( $L_{Aeq_n}$ ) metric descriptors.

**KEYWORDS:** Fuzzy logic systems, Annoyance, Metrics, Aircraft noise.

## INTRODUCTION

Noise exposure arising from air traffic has been the main cause of conflicts between airports and nearby communities in most major cities around the world.

A paper entitled “Synthesis of social surveys on noise annoyance” has been seminal in a series of social research papers that summarize the annoyance data associated between the Day-Night Level metrics (*DNL*) and the number of highly annoyed people (Schultz, 1978).

The *DNL* metrics is associated to the average sound energy produced by the summation of aeronautical events over a 24-hour period, whence a 10 dB(A) penalty weighting is applied during the night. Until recently, the methodology used to assess the percentage of people who were highly annoyed by noise was inspired by Schultz’s proposal.

On the other hand, a new methodology based on fuzzy logic evaluation of criteria levels that take into account the community comfort according to the Brazilian Standard ABNT/NBR 10151 was proposed, establishing a relationship between the percentage of highly annoyed people by adverse noise effects around the airport, and  $L_{Aeq_d}$  and  $L_{Aeq_n}$  metrics.

## EVOLUTION OF STUDIES ON NOISE ANNOYANCE CAUSED BY AIR TRANSPORTATION

Research about exposure to aircraft noise began in the United States with the introduction of the jet aircraft in military bases in the 1950’s. This led to the publication of original scientific papers which examined the exposure of the population to aircraft noise, which, in turn, paved the way to community response around airports. In the 1970’s,

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the increased transportation noise coaxed extensive studies on the relationship between traffic flow, noise emission and community reaction (Fidell et al., 1988).

The Environmental Protection Agency (EPA) later related the complaint and annoyance data with the noise exposure level through of a dose-effect relationship, presenting an interpretation of the annoyance caused by sound levels with the *DNL* metrics, with terms widely used to evaluate the environmental noise in the community.

Nevertheless, it is worth noting that EPA did not relate the noise effects to people's health, stress and hearing loss, restricting instead its recommendations to interference and annoyance activities while using the term *community reaction* when referring to complaints (EPA, 1974).

Finally, by using a linear regression of social surveys in the neighborhood of airports, EPA developed a function correlating population response and noise levels, thus yielding from the following equation (Eq. 1) the percentage of highly annoyed (*HA*) people.

$$\%HA = 1.8(DNL - 4.6) \quad (1)$$

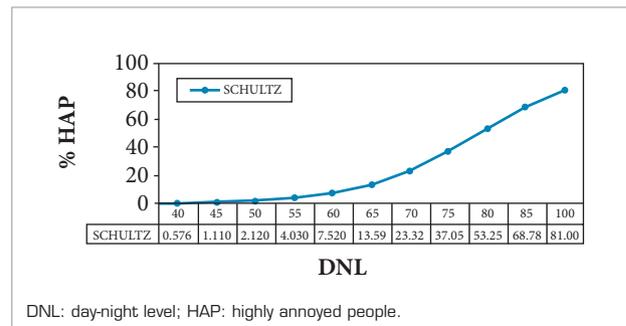
But before this study, the approach to characterize adverse reactions to aircraft noise was centered on complaint prediction, complaints alone, and behavioral consequences.

### SCHULTZ CURVE: RELATION BETWEEN DNL AND HIGHLY ANNOYED PEOPLE (HAP)

In 1978, Schultz proved that aircraft noise in different cities may be interpreted in a dose-effect relationship. Such original research procedures were based on various noise transportation studies (air, rail and roadways), as well as on the fragmentation between neighborhoods evenly exposed to noise in different degrees, and significantly impacted by noise in adjacent areas.

The curve shown in Fig. 1 yields a reasonable expression for the relationship between noise level and community response, and such graphic enables the quantification of the highly annoyed people percentage according to the level of exposure to noise in the community.

Based on data from social surveys, Schultz proposed an equation (Eq.2), relating the percentage of *HAP* with *DNL* metrics. He describes his research group by using a third degree polynomial function in an informal approach rather than a relation derived from linear regression analysis, and



**Figure 1.** Relation between day-night level metrics and % highly annoyed people.

this equation now allows to estimate %*HAP*, the percentage of *HAP* exposed to certain noise levels.

$$\%HAP = 0.8533DNL - 0.0401DNL^2 + 0.00047DNL^3 \quad (2)$$

### THE INFLUENCE OF SCHULTZ'S ANALYSIS

Afterwards, the publication of Schultz's results was followed by an update of its original curve whence a wider database was used to predict the annoyance caused by the exposure to transportation noise. In this update, a quadratic function was chosen instead of Schultz's cubic curve, as shown in Eq. 3 (Fidell et al., 1988).

$$\%HA = 78.9181 - 3.2645DNL + 0.0360DNL^2 \quad (3)$$

By reanalyzing the data from Fidell et al. (1988), Finegold et al. (1994) eventually published the results of a new meta-analysis that recommended the following equation to predict annoyance based on the final 400 data points and dose-response relationship, as shown in Eq. 4.

$$\%HA = \frac{1}{1 + e^{(11.13 - 0.14DNL)}} \quad (4)$$

### THE CONTROVERSY OF SCHULTZ'S ANALYSIS

Although Schultz's results may be regarded as conventional scientific knowledge, his study remained controversial for years. While widely accepted in literature circles, it was strongly based on his personal prediction curves for community annoyance caused by transportation noise (Kryter, 1982).

Initially, Schultz' surveys to assess annoyance were conducted in various manners, with the conversion of metrics to *DNL* noise levels, thus leading to much objection — especially

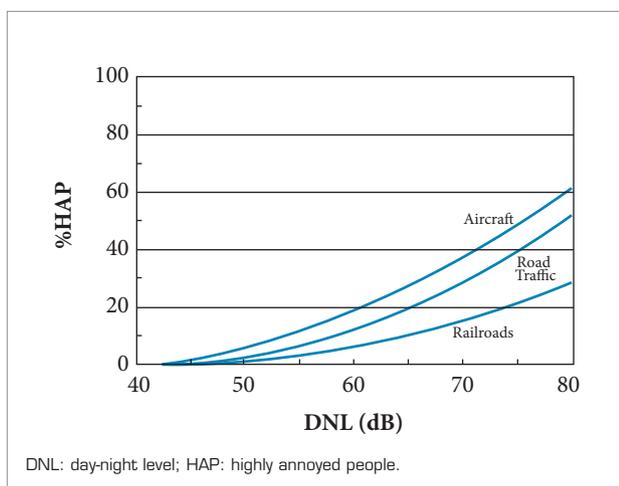
concerning the adoption of a personal definition of annoyance as a variable depending on its dose-effect relationship.

Beside his procedures, Schultz's subjective judgment to determine values that best corresponded to the term highly annoyed encountered strict criticism from sociologists, who accused him of manipulating results and questioned his lack of scientific definition in coining the term 'highly annoyed', which eventually resulted in repeating procedures for the researcher in order to obtain the same results.

Other researchers finally contested the choice of a single relationship synthesizing sources in transportation noise: Schultz' curve represents the average community response to three sources of transportation noise (air, rail & roadways). Is it possible for the same curve to represent the same noise annoyance caused by different transportation sources?

Miedema and Vos (1998) analyzed the level of noise annoyance caused by each source of transportation noise separately, listing the percentage of highly annoyed and  $DNL$  for each of them, as shown in Fig. 2. Such curves display a systematic difference between the three sources of transportation noise and show that, in general, aircraft noise causes more annoyance than that of roads or railways.

These problems with Schultz's analysis have been widely discussed in specialized circles. In this paper, we will emphasize the choice of  $DNL$  metrics; its capacity to estimate the percentage of  $HAP$  due to noise transportation; and its association with a weighted average sound energy produced



**Figure 2.** Value of highly annoyed people versus day-night level for each source of transportation noise.

by all aircraft events that occurred in the last 24-hour period. This metric is given by Eq. 5.

$$DNL = 10 \log_{10} \left\{ \frac{1}{3600 \cdot 24} \left[ \int_7^{22} 10^{L_A(t)/10} dt + \int_{22}^7 10^{L_A(t)+10/10} dt \right] \right\} \quad (5)$$

However, such metrics is not appropriate to represent annoyance in airports in which, despite the 10dB(A) correction, night time use restrictions exist, and because it is not the same as to separately consider the contribution of noise exposure between day and night-time.

## METHODS AND DATA

### FUZZY MODELING TO ASSESS NOISE ANNOYANCE

In the Brazilian legislation, acoustic comfort is assessed separately during day and night-time because adverse effects are different depending on the nature of the noise (ABNT/NBR 10151). Annoyance begins when comfort is lost, and noise exposure should be evaluated separately during daytime and night-time.

Hence, if one is to consider the use of  $L_{Aeq_D}$  and  $L_{Aeq_N}$  to represent annoyance during day and night-times, this metrics will define a new airport zone and provide a clear set of application curves to urban authorities, which will find their use to produce a compatible urban zone. Such metrics will also be more appropriate to assess the adverse effects of noise.

$L_{Aeq_D}$  is defined as the average sound energy of events that took place between 7h and 22h, as demonstrated in Eq. 6.

$$L_{AeqD} = 10 \log_{10} \left[ \frac{1}{3600 \cdot 15} \int_7^{22} \frac{P_a^2(t)}{P_0^2} dt \right] \quad (6)$$

$L_{Aeq_N}$  is defined as the sound energy of events that took place between 22h and 7h, as demonstrated in Eq. 7.

$$L_{AeqN} = 10 \log_{10} \left[ \frac{1}{3600 \cdot 9} \int_{22}^7 \frac{P_a^2(t)}{P_0^2} dt \right] \quad (7)$$

This paper presents an alternative approach based on fuzzy logic to estimate the percentage of HAP due to aircraft noise that uses  $L_{AeqD}$  and  $L_{AeqN}$  metrics as input variables, whence annoyance is the output.

Revoredo and Slama (2008) have shown results on the use of the DNL metrics according to  $L_{AeqD}$  and  $L_{AeqN}$  metrics, as shown in Eq. 8.

$$DNL = 10 \log_{10} \left[ \frac{1}{24} \left( 15 \cdot 10^{\frac{L_{AeqD}}{10}} + 90 \cdot 10^{\frac{L_{AeqN}}{10}} \right) \right] \quad (8)$$

Basic fuzzy logic concepts are presented in the next section.

**PRINCIPLES AND ELEMENTS OF FUZZY LOGIC**

Fuzzy logic was developed by Zadeh (1965). A fuzzy set  $F$  defined over a universe of discourse  $X$  is characterized by a membership function  $mF(x)$  which assumes values in the interval  $[0, 1]$ .

A fuzzy set is a generalization of a classical set (crisp set) whose membership function assumes only two values, zero or one. Thus, if  $X$  is the universe of discourse and its elements are denoted by  $x$ , then a fuzzy set  $A$  in  $X$  is defined as a set of ordered pairs:

$$A = \{x, \mu_A(x) / x \in X\}$$

Where  $m_A(x)$  is the membership function of  $x$  in  $A$ , that assigns a membership degree between 0 and 1 to each element of  $X$ .

Fuzzy conditional states the form IF  $A$  THEN  $B$ , where  $A$  and  $B$  are terms with a fuzzy meaning, e.g., “IF day night sound level is high, THEN people are highly annoyed”. These rules can be presented below:

Antecedent:  $x$  is to  $A'$  as  $y$  is to  $B'$   
 Rule ( $R_i$ ): If  $x$  is  $A_i$  and  $y$  is  $B_i$  then  $z$  is  $C_i$   
 Consequently:  $z$  is  $C_i$

Where  $x$  and  $y$  are linguistic variables related to the fuzzy model and  $z$  is the output linguistic variable.  $A', A_i, B', B_i, C_i, C_i$  are fuzzy sets of the  $x, y$  and  $z$ .

Fuzzy algorithm is an ordered sequence of instructions in which some of the instructions may contain labels of fuzzy sets (Zadeh, 1973).

So, each rule is a fuzzy conditional statement and different fuzzy relations can derive from this.

The implementation of each rule is made by defining operators to process the input variables. The involvement function will set the output variable.

Fuzzy logic system is the nonlinear mapping of an input data vector into a scalar output (Mendel, 1995). The fuzzy system is defined by the aggregation of rules that make up the fuzzy algorithm through the use of connectives such as “IF”, “THEN”.

**LINGUISTIC MODIFIERS OR HEDGES**

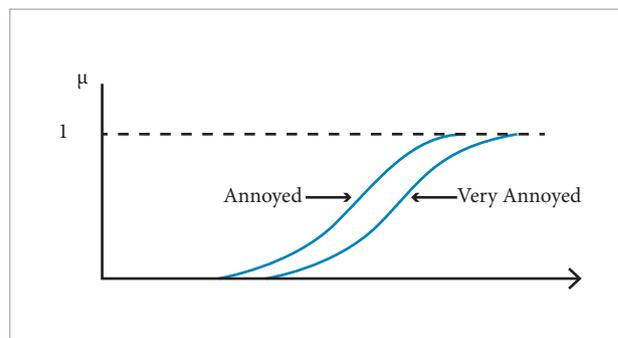
From a fuzzy subset, through the linguistic modifiers, it's possible to generate other subset of values for a linguistic variable from a small collection of primary terms. For the assessment of environmental impact, hedges or linguistic modifiers are a benefit that allows the adjustment to local values (Shepard, 2005).

A hedge  $h$  can be considered as an operator that modifies the fuzzy set  $M(u)$ , representing the meaning of  $u$ , into the fuzzy set  $M(hu)$  (Zadeh, 1973b). Applied to fuzzy sets, hedges are modifiers that concentrate or dilute the support range of the fuzzy set. In other words, the hedge changes the shape of the membership curve so that support set values have a different range for the inclusion in the fuzzy set.

Thus, according to Zadeh (1973), the “very” operator acting in a fuzzy set labeled  $x$ , this effect is shown in Fig. 3.

So, using the modifier “very” together with “not”, and the primary term *annoyed*, we obtain the fuzzy sets: *very annoyed*, *not very annoyed*. The modifier *very* is defined by:

$$very\ x \triangleq x^2$$



**Figure 3.** Effect of hedge “very”.

The symbol  $\triangleq$  stands for “equal by definition”.

The modifiers “plus” and “minus” were used with the intention to decrease the degree related to concentration and dilation. Thus, operators acting in a fuzzy set labeled  $x$ , “plus” and “minus” are defined by:

$$\begin{aligned} \text{Plus } x &\triangleq x^{1.25} \\ \text{Minus } x &\triangleq x^{0.75} \end{aligned}$$

Then:

$$\text{Plus Plus } x = \text{minus very } x$$

Thus modifier “highly” has been defined as:

$$\text{highly} = \text{minus very very} = x^{0.75} \cdot x^2 \cdot x^2 = x^3$$

### FUZZY LOGIC AND NOISE ANNOYANCE

The fuzzy logic is characterized by its ability to infer conclusions and generate responses from vague information, which is ambiguous, qualitatively incomplete and inaccurate. Its use is very simple and natural, leading to the construction of understandable systems that are easy to maintain.

The noise annoyance can be associated with objective variables, but mostly to subjective variables.

So, noise annoyance can be modeled by a fuzzy system. In this paper, the fuzzy system will assign a crisp value to a particular annoyance situation. In other words, a real number that represents the percentage of people disturbed by aircraft noise.

The fuzzy model developed here aims to assess annoyance caused by aircraft noise with  $L_{Aeq_D}$  and  $L_{Aeq_N}$  metrics.

ABNT/NBR 10151/1987 Standard uses  $L_{Aeq_N}$  to define the sound levels during daytime and night-time. It introduces a classification that relates the estimated response of the community to noise as shown in Table 1. In essence, it is presented as a fuzzy system because each addition to level criterion corresponds to a response category.

According to the table, some fuzzy linguistic terms were chosen. Thus, we will use these sound levels as a reference to estimate the annoyance through fuzzy logic, since the standard establishes a comfort level for different areas, such as: residential, mixed and industrial areas.

### FUZZY MODEL DESCRIPTION

The fuzzy model was developed from a computational tool provided by the Fuzzy Logic toolbox, MATLAB version 7.0. Fuzzy model is described below.

#### Fuzzification

The fuzzy system consists of choosing input and output variables and determining for each of them which fuzzy subsets are associated with linguistic variables.

Linguistic variables are ideally suited to express the concepts found in environmental impact assessments (Shepard, 2005).

Linguistic variables can be defined by linguistic terms. In others words, these variables contain descriptive fuzzy terms, which represent a range within the variable.

In this work,  $L_{Aeq_D}$  and  $L_{Aeq_N}$  were defined as input variables, and annoyance is the output variable. The fuzzy linguistic terms were estimated according to the sound levels adopted by the ABNT/NBR 10151/1987.

The linguistic terms used to represent the fuzzy subsets of  $L_{Aeq_D}$  and  $L_{Aeq_N}$  were “very low”, “low”, “medium”, “high”, “very high”. And the linguistic terms used to characterize output variables were “null”, “small”, “moderate,” “strong” and “verystrong”.

Linguistic terms were defined according to the Brazilian standard ABNT/NBR 10151/1987. When sound level exceeds the level criterion, there is an estimated response of the community to noise.

### MEMBERSHIP FUNCTION

A triangular fuzzy set might be used to create a fuzzy number from a measured, crisp value, but otherwise it would not represent the underlying semantics of the variable.

**Table 1.** Community's response to noise.

Values [dB(A)] by which the sound level exceeds the level criterion ( $\Delta$ )	Estimated response of the community	
	Category	Description
0	Null	No reaction
5	Small	Sporadic complaints
10	Moderate	Widespread complaints
15	Strong	Community Action
20	Very strong	Strong community action

Sigmoid and bell-shaped membership curves are extensively used in the environmental impact assessment to represent the meaning of measured components in the existing environment and predicted changes for alternatives (Shepard, 2005; Eller, 2009).

In the model proposed, triangular membership curves were used for input variables and bell-shaped membership curves for output ones.

### Implication and Aggregation Rules

Fuzzy sets are created by the application of the rule base and aggregation methods. These fuzzy sets reflect the degree of truth contained in the model and how well the model's rules respond to the model's input data.

According to the input and output variables, 25 rules were developed. To illustrate, we have:

Rule 1: IF  $L_{AeqD}$  is very low and  $L_{AeqN}$  is very low, THEN the annoyance is null.

Rule 2: IF  $L_{AeqD}$  is very high and  $L_{AeqN}$  is low, THEN the annoyance is very strong.

By using this fuzzy system, the annoyance has been related to the response estimated population for different combinations of  $L_{AeqD}$  and  $L_{AeqN}$  in accordance with acceptable sound levels for each kind of residential areas of ABNT/NBR 10151.

### Defuzzification

Latest, we have to choose the defuzzification method to convert fuzzy statements into a crisp value in order to obtain the percentage of annoyed people. The defuzzification process was performed by the centroid method.

We consider the sound levels of ABNT/NBR 10151 as a condition of acoustic comfort, particularly in the case of residential use.

In this work the ABNT/NBR 10151 received more emphasis for residential use: "Strictly Urban, Residential, School or Hospital Areas" – with  $L_{AeqD}$  =50 and  $L_{AeqN}$  =45 and "Predominantly Residential Mixed Areas" – with  $L_{AeqD}$  =55 and  $L_{AeqN}$  =50.

In the first condition, *Strictly Urban, Residential, School or Hospital Areas* with  $L_{AeqD}$  =50 and  $L_{AeqN}$  =45, sound levels are compatible to a condition of acoustic comfort.

While sound levels increase, they are no longer compatible with residential use and, gradually, annoyance appears.

The same was done to the second condition, *Predominantly Residential Mixed Areas* with  $L_{AeqD}$  =55 and  $L_{AeqN}$  =50.

Figure 4 presents an example of the windows that open in the toolbox, in which we insert the  $L_{AeqD}$  and  $L_{AeqN}$  values and obtain the annoyance percentage. In this work, various combinations of  $L_{AeqD}$  and  $L_{AeqN}$  were simulated. On the other hand, we need the percentage of the HAP, so we applied the modifier "highly" in the annoyed function.

### Hedge

The hedge has been used to generate the subset "highly annoyed" from the subset "annoyed". So, according to Zadeh's proposal, the "highly annoyed" function corresponds to a cubic function applied to "annoyed people".

## RESULTS

### ANALYSIS OF RESULTS ACCORDING TO THE BRAZILIAN STANDARD ABNT/NBR 10151

Fuzzy model is a representation of the Standard ABNT/NBR 10151/2000, whose results relate sound levels that exceed the level criterion with the estimated response of the community. This standard was based on World Health Organization's (OMS) results, present in the publication Guidelines for Community Noise (WHO, 1999).

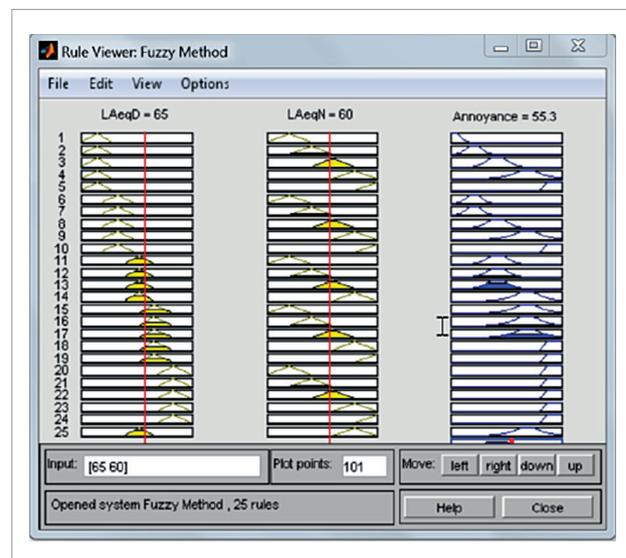


Figure 4. Window of the toolbox Fuzzy with input and output values.

Schultz's results were obtained from Eq. 3, which related the percentage of *HAP* to *DNL* metric. The results are presented in Tables 2 and 3.

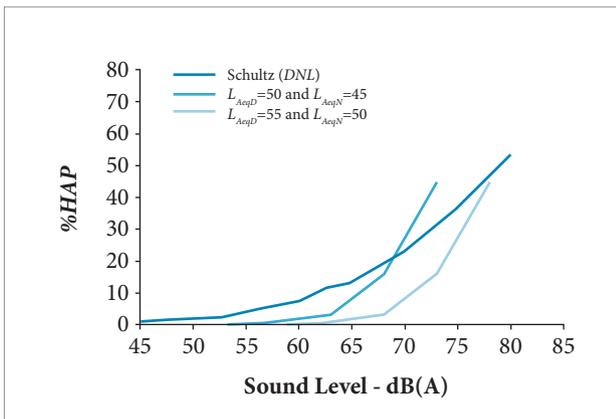
The curves have the same behavior, with a single horizontal shift of 5 dB (A) between them, as shown in Fig. 5. From a certain noise level, the percentage of *HAP* obtained from the fuzzy modeling grows at a rate higher than the Schultz's curve, depending on the type of area.

**Table 2.** Residential condition: *Strictly Urban, Residential, School or Hospital Areas* with  $L_{Aeq_D}=50$  and  $L_{Aeq_N}=45$ .

$\Delta$	$L_{Aeq_D}$	$L_{Aeq_N}$	HAP (%) Fuzzy
0	50	45	0.03
5	55	50	0.98
10	60	55	3.22
15	65	60	15.92
20	70	65	44.42

**Table 3.** Residential condition: *Predominantly Residential Mixed Areas* with  $L_{Aeq_D}=55$  and  $L_{Aeq_N}=50$ .

$\Delta$	$L_{Aeq_D}$	$L_{Aeq_N}$	HAP (%) Fuzzy
0	55	50	0.03
5	60	55	0.98
10	65	60	3.22
15	70	65	15.92
20	75	70	44.42



**Figure 5.** Curves obtained from fuzzy model to %HAP in each condition.

The percentage of *HAP* (slowly increasing) is low for low levels, because noise levels are appropriate for this use. However, for higher levels the percentage of *HAP* grows significantly.

Residents in *Strictly Urban, Residential, School or Hospital Areas* with  $L_{Aeq_D}=50$  and  $L_{Aeq_N}=45$  are used to very low noise levels. Therefore, this condition (blue curve) is more appropriate to assess the annoyance.

Both curves show an abrupt increase of the curve inclination, which is coherent with the shape of noise perception by humans according to WHO for high levels. Usually, annoyance comes earlier, and the perception depends on environmental noise level and type of area.  $L_{Aeq_D}$  and  $L_{Aeq_N}$  levels are used to character a region in accordance with the assessment criterion level.

The fuzzy model developed to evaluate the noise annoyance takes into account the daytime and night-time noise levels for each area. As a consequence, %*HAP* was obtained for various situations.

## CONCLUSION

The fuzzy system assessing aircraft noise annoyance is based on a set of logical conditions that follow noise level recommendations in residential areas defined by ABNT/NBR 10151. The estimated community response to noise considered in the previous version of this Standard was important to define the variables of the fuzzy model.

The fuzzy model relates the  $L_{Aeq_D}$  and  $L_{Aeq_N}$  noise metrics and the percentage of *HAP* to evaluate the annoyance using fuzzy logic.

For low values of noise levels, the predicted annoyance will be less than that proposed by Schultz, while for higher levels, the annoyance predicted will present a much greater value than that in Schultz's model.

The term "highly annoyed" has been used according to the definition proposed by Zadeh, and this tool is appropriate to adjust the values.

The choice of triangular membership functions is valid to  $L_{Aeq_D}$  and  $L_{Aeq_N}$  variables due to the fact that such functions can be easily adjusted through an optimization process based on genetic algorithms.

For the variable annoyance, bell-shaped membership curves were used, since they are more appropriate to

represent the noise annoyance in cases of the assessment of environmental impact.

From the methodology presented herein, it is possible to develop fuzzy systems for environmental impact assessment from other sources of noise.

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