Psychoacoustic evaluation of a garden tractor noise

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Abstract: Agricultural machine operators are exposed to a number of occupational health and safety risks. Noise is considered as one of the most common occupational health hazards in farming activities. Aim of this study is to evaluate acoustical comfort and the noise levels exposed on the operators of the garden tractor. For this purpose, some factors were evaluated which affect the noise generated by a Goldoni garden tractor. Research factors were including engine speed, gear ratios and type of operation. During measurement and recording the sound signals of the garden tractor, the variables of engine speeds and gear ratios were varied to cover the most normal range of the garden tractor operation in tillage condition and transportation condition on the rural road. Accordingly, factorial experiments were performed in completely randomized design with three replicates. According to variance analysis with LAeq, PA and UBA, operation type, gear ratio and engine speed were found significant ($P< 0.01$). The results show that LAeq, PA and UBA for rural road are higher than tillage condition. Also, results indicated that the highest mean of LAeq, PA and UBA were 77.76dBA, 9.83 and 21.16, respectively and occurred in the case of rural road and 2100 r/min engine speed. The results of this study indicate that PA and UBA correlated strongly with LAeq analysis (R2=0.97).Therefore, the LAeq, obtained in this research, will be a good indicator of the PA and UBA.

Keywords: garden tractor, psychoacoustic, sound quality, sound pressure level

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1 Introduction

Sustainable development of agricultural mechanization has caused problems on occupational health and safety for people working in different fields of agriculture. Using agricultural machinery results some ergonomic problems such as noise. Noise is generally defined as unwanted or bothersome sounds which can affect people in physical, psychological and social dimensions, namely by causing auditory lesions, stress, annoyance, distraction, tiredness or simply by impairing social communication (Freitas et al., 2012; Gorai et al., 2006; Klaeboe, 2011). Also, it can induce temporary or permanent hearing losses (Levicitus and Sampton, 1993).

The sound as a physical phenomenon can be described by acoustics quantities such as sound pressure level, fundamental frequency or frequency spectrum. Sound pressure level is a term most often used in measuring the magnitude of sound. It is a relative quantity in which there is a ratio between the actual sound pressure and a fixed reference pressure. This reference pressure is usually the threshold of hearing which has been internationally agreed upon as having the value 20 µPa at 1 kHz.

Sound pressure level is a logarithmic measurement of the effective sound pressure and it is measured in decibels (dB) above the standard reference level. The frequency response of the human ear must be considered when addressing the effect of noise on people. Human being does not perceive low and high frequency sounds as well as they perceive sounds near 2–4 kHz. Sound measuring instruments are often designed to weight sounds based on the way people hear. The frequency weighting most often used to evaluate environmental

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noise is A-weighting. The measurements from instruments using A-weighting system are reported in dBA.

Another problem in vehicle acoustics concerns acoustic comfort, not hearing damage. In the evaluation of the acoustic comfort of a sound, fundamental quantities such as acoustic sound pressure level are not adequate to truly represent the actual hearing sensations. The science of psychoacoustics involves the quantitative evaluation of these subjective sensations using sound quality metrics. Application of sound quality metrics allows the visualization of the complicated relationship between the physical and perceptual acoustic quantities (Novak et al., 2004). There are several sound quality metrics which used in evaluate vehicle induction noise. These metrics included loudness, sharpness, roughness, fluctuation strength and articulation index (Fastl and Zwicker, 2007).

Noise issues and its influence on agricultural sector has been considered for many years and today, it has been investigated the various aspects of it. Certainly people who are working in various agricultural affairs exposed to a lot of other noise sources and it has not fully specified all the risks for people who have long been exposed to the noise, yet (McBride and Herbison, 2003). In comparison to the other occupations, agricultural workers have higher rates of hearing loss. Because there are a lot of noise generators in the field such as tractor, combine, chopper, chain saw, dryers, etc. (Baker, 2002). Several studies have been conducted to analyze the effect of objective sound level (Zamanian et al., 2012; Aliabadi et al., 2012; Monazzam et al., 2012) and subjective sound level on the operator's performance (Li and Zuo, 2013; Nakasaki et al., 2008; Wang, 2009).

The objectives of this study were:

– To determine and compare the noise levels exposed on the operators of the garden tractor under different operative conditions. For this purpose, equivalent A-weighted sound pressure level of a model 341 Goldoni garden tractor was measured.

– To evaluate acoustical comfort of garden tractor according to psychoacoustic annoyance and unbiased annoyance.

– To determine the relation between sound pressure level and acoustical comfort in order to predict psychoacoustic annoyance and unbiased annoyance based on sound pressure level.

2 Materials and methods

This study deals with determining and comparing the noise exposed on the operators of the garden tractor. There were measured the A-weighted sound pressure level and psychoacoustic annoyance and unbiased annoyance were calculated at the ear level of the operators on Goldoni 341 garden tractor. It is showed the specification of used garden tractor in Table 1.

Table 1 Garden tractor specifications

Engine	
Power	41 hp
Cylinder	3
Volume	1649 cc
Torque, max.	113 Nm
Transmission	
Type	Manual
Forward speed, max.	18.8 km/h
Gears, forward/reverse	6/3

2.1 Statistical analysis

Factorial experiments were conducted in the form of a completely randomized design with three replications. The factors include the engine speed at five levels of 1000, 1300, 1600, 1900 and 2100 r/min, different gear ratios in four levels of neutral, first, second and third and operation type in two levels of rural road and tillage. The data were read by MATLAB software and they were analyzed using SPSS software.

2.2 Instrumentation scheme

In order to measure the noise level of the tractor at the operator's ear, the microphone placed at a distance of

100 mm relative to the operator's ear. Figure 1 shows the microphone position at the operator's ear.

Figure1 Garden tractor and microphone position at the operator’s ear

The test location characteristics considered based on the ISO standard (ISO 5131, 1996). For this purpose a free field selected with a suitable distance from buildings and trees. During the test, wind speed was less than 5 m/s and the temperature of the ambient air was more than 5 ℃, according to the standard.

In this research, measuring equipments were: MIC model MA231, MP201 model amplifier and data acquisition system model MC3022 which all made by BSWA. The considered microphone is a type 1.This microphone has a sensitivity of 50mV/Pa and a dynamic range of 146 dB (3% distortion limit). The received signal saved on a laptop computer, using Scope V1.32 software. Microphones were calibrated by calibrator model CA111, which creates 94 dB the constant sound level in a pure frequency 1 kHz, before beginning the measurement. Calibrator should be selected the type 1 because the selected microphone was type 1, which is based on IEC standard (IEC 60942, 2003). In every composition of treatment, it was recorded at least 5 s sound signal. Figure 2 shows a typical signal in time domain.

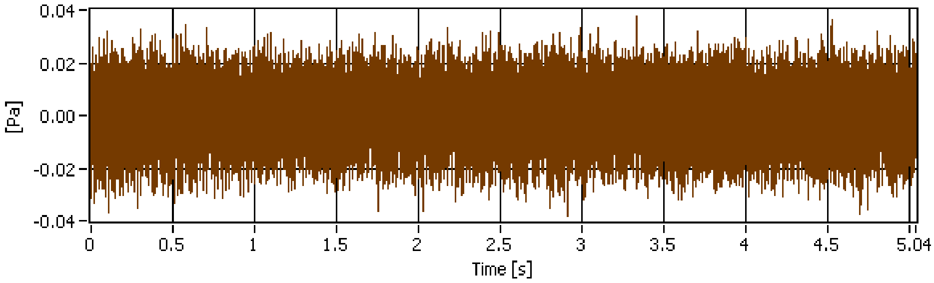

Figure2 Typical sound pressure signal in time domain for garden tractor

2.3 A-weighted sound pressure level

The ISO 1999(1990) provides a definition for the equivalent A-weighted sound pressure level in dBA, identified as L_{Aeq}. This function gives the value of the A-weighted sound pressure level of a continuous, steady sound, within a specified time interval T, which has the same mean square sound pressure as the sound under consideration whose level varies with time. It is expressed with the below Equation 1:

$$L_{Aeq} = 10 \log\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2}dt\right] \qquad (1)$$

Where L_{Aeq} is the equivalent continuous A-weighted sound pressure level, in dBA, determined over a time interval T starting at t_1 and ending at t_2, p_0 is the reference sound pressure (20 microPascal) and $p_A(t)$ is the instantaneous A-weighted sound pressure of the sound signal.

2.4 Loudness

Loudness represents the auditory perception character related to the magnitude of the sounds (Lee et al., 2006). Since human ear has different sensitivities to different frequencies, loudness is very important for the evaluation of exposure noise (Zwicker and Fastl, 1990). Stevens and Zwicker are two procedures usually considered for physical loudness measurements. Zwicker loudness in comparison with Stevens loudness reflects most of the psychoacoustic properties of the human perception of the sound. Due to robustness of Zwicker loudness, this loudness assessment procedure has been standardized in several computer programs and sound level meters. According to the standard ISO 532B(1975), the specific loudness of a sound N' is defined as Equation 2 (Fastl and Zwicker, 2007):

$$N' = 0.08\left(\frac{E_{TQ}}{E_0}\right)^{0.23}\left[\left(0.5+0.5\frac{E}{E_{TQ}}\right)^{0.23}-1\right] \qquad (2)$$

Where E is excitation of the sound, E_{TQ} is excitation in the quiet ambient and E_0 is excitation under a reference sound with intensity of $I_0=10^{-12}W/m^2$.

The total loudness N (in 'sone') can be calculated by Equation 3 (Fastl and Zwicker, 2007):

$$N = \int_0^{24} N'(z)dz \qquad (3)$$

Where z is critical band rate in Bark. Human ear combines sound stimuli situated close to each other in frequency domain in a single frequency band. These bands are called as critical bands. The audible range divided by Zwicker into 24 critical bands with a scale called 'Critical band rate'. It is measured in the units of 'Bark'(Kadlaskar, 2010).This scale is more equivalent to features of human hearing system than frequency (Fastl and Zwicker, 2007).

2.5 Sharpness

Sharpness is a hearing sensation related to the frequency. Sharpness corresponds to the sensation of a sharp and painful sound and is a measure of the high frequency content of a sound (Muller and Moser, 2013). There are several procedures of sharpness computation. They differ mainly in definition of weighing functions. The total sharpness S in 'acum' is defined as Equation 4 (Fastl and Zwicker, 2007):

$$S = 0.11\frac{\int_0^{24} N'(z)\,g(z)\,z\,dz}{\int_0^{24} N'(z)\,dz} \qquad (4)$$

Where $g(z)$ is weighting function. Implemented weighting function is Equation 5:

$$g(z) = \left\{\begin{matrix} 1 & for\ z \le 16 \\ 0.066\ e^{0.171z} & for\ z > 16 \end{matrix}\right\} \qquad (5)$$

2.6 Fluctuationstrength

Perception of fluctuation strength is especially important in terms of unpleasantness of sounds. Fluctuation strength quantifies subjective perception of slow (up to 20Hz) amplitude modulation of a sound (Yanagisawa et al., 2007). Fluctuation strength F in 'vacil' is defined as Equation 6 (Fastl and Zwicker, 2007):

$$F = \frac{0.008\int_0^{24} \Delta L(z)dz}{\left(f_{mod}/4\right)+\left(4/f_{mod}\right)} \qquad (6)$$

Where f_{mod} is modulation frequency and ΔL is masking depth is defined as Equation 7 (Chatterley et al., 2006):

$$\Delta L(z) = 4\ log\left(N'_{max}/N'_{min}\right) \qquad (7)$$

Where N'_{max} and N'_{min} are percentile loudness values. Figure 3 shows illustration of fluctuation strength, modulation frequency and the perceived masking depth.

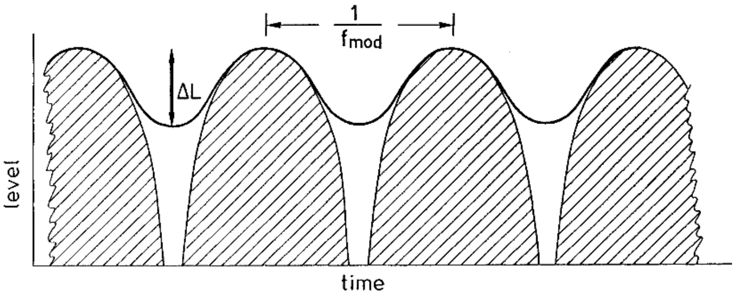

Figure3 Illustration of fluctuation strength and corresponding modulation frequency and masking depth

2.7 Roughness

Roughness is a fundamental hearing sensation for fast (between 15 to 300Hz) amplitude modulations. It is an important parameter for the assessment of the perceived quality of the sounds (Havelock et al., 2008). This metric correlates to how noticeable or annoying a sound is as heard by the human ear. The formula for roughness calculation was first given by Zwicker. The roughness R in 'asper' is as Equation 8 (Fastl and Zwicker, 2007):

$$R = 0.3\, f_{mod} \int_{0}^{24} \Delta L_E(z)\, dz \qquad (8)$$

ΔL_E is defined as Equation 9 (Chatterley et al., 2006):

$$\Delta L_E(z) = 20\, \log\left(N'_{max} / N'_{min} \right) \qquad (9)$$

Figure 4 shows typical set of specific loudness, sharpness, roughness and fluctuation strength.

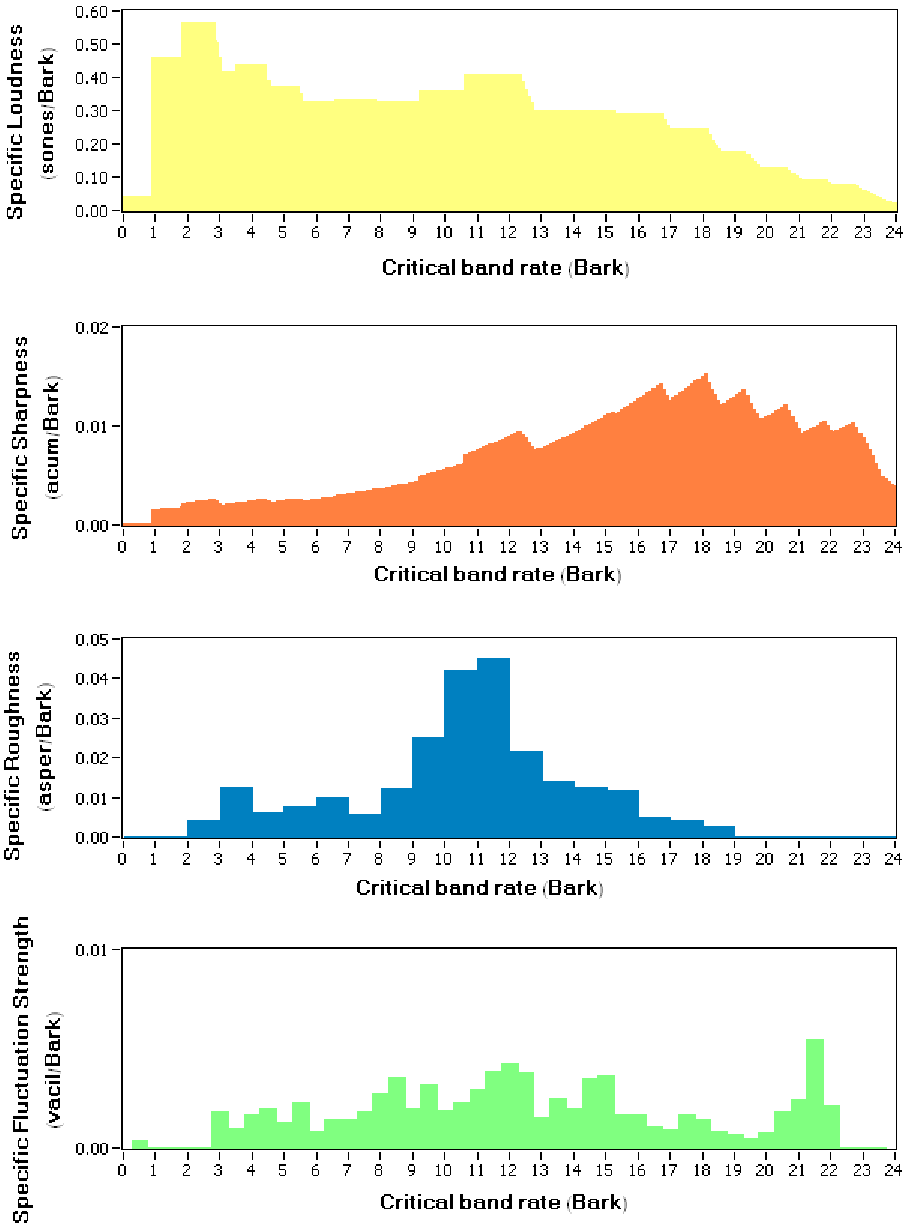

Figure 4 Specific loudness, sharpness, roughness and fluctuation strength for garden tractor

2.8 Unbiased annoyance (UBA)

The unbiased annoyance model is a function of 10% loudness (N_{10}), sharpness (S) and fluctuation strength (F) of the sound together with a day-night correction (d). The formula for UBA reads as Equation 10 (Kaczmarek and Preis, 2010):

$$UBA = d\left(N_{10}\right)^{1.3}\left(\begin{array}{l}1+0.25\left(S-1\right)\log\left(N_{10}+10\right)\\ +0.3\left(F\dfrac{1+N_{10}}{N_{10}+0.3}\right)\end{array}\right) \qquad (10)$$

The percentile loudness N_{10} is the loudness that is exceeded in ten percent of the time of the measurement duration and was calculated by statistical analysis using Microsoft Excel. Day/night factor is defined as Equation 11:

$$d=\left\{\begin{array}{ll}1 & 6\ am\ to\ 10\ pm\\ 1+\left(\dfrac{N_{10}}{5}\right)^{0.5} & 10\ pm\ to\ 6\ am\end{array}\right\} \qquad (11)$$

2.9 Psychoacoustic annoyance (PA)

There is another approach which allows neglecting the noise sensitivity problem. This approach was proposed for the first time by Zwicker and Fastl (1990) and was called psychoacoustic annoyance. The value of PA is calculated from N_5 loudness (the loudness value reached or exceeded in 5% of the measurement time and calculated by statistical analysis), sharpness (S), roughness (R) and fluctuation strength (F) together. In comparing to the UBA, in the new formula N_{10}ischanged to N_5 and roughness is added as a component of psychoacoustic annoyance. The formula for psychoacoustic annoyance reads as Equation 12 (Zwicker and Fastl2007):

$$PA = N_5\left(1+\sqrt{\omega_S^2+\omega_{FR}^2}\right) \qquad (12)$$

Where N_5 is percentile loudness in sone. See Equation 13 and Equation 14:

$$\omega_S=\left(S-1.75\right)0.25\ \log\left(N_5+10\right) \qquad for\ S > 1.75\ acum$$

$$\omega_S= 0 \qquad for\ S < 1.75\ acum$$

$$\omega_{FR}=\frac{2.18}{\left(N_5\right)^{0.4}}\left(0.4F+0.6R\right) \qquad (14)$$

3 Results

Table 2 shows the effects of operation type, gear ratio and engine speed on sound quality metrics, L_{Aeq}, PA and UBA as obtained through analysis of variance for garden tractor. Figure 5 shows sound quality metrics at different gear ratio and engine speed. In this figure, each value on the left panels is an average over all engine speeds and all operations, and each value on the right panels is an average over gear ratios and operations.

Table 2 Analysis of variance of data on measured parameters

Source	df	Mean Squares						
		L_{Aeq} (dBA)	Loudness (sone)	Sharpness (acum)	Roughness (asper)	F.Strength (vacil)	PA	UBA
Operation	1	52.550**	9.331**	0.285**	6.675E-05^{ns}	0.10*	7.179**	81.786**
Gear	3	36.104**	6.936**	0.0002^{ns}	0.007**	0.018**	16.289**	113.077**
Speed	4	228.294**	42.009**	0.661**	0.054**	0.003^{ns}	72.887**	535.361**
Operation ×Gear	3	0.556^{ns}	0.139^{ns}	0.006^{ns}	0.013**	0.009*	0.633^{ns}	3.826^{ns}
Operation ×Speed	4	5.046*	0.837*	0.067**	0.001^{ns}	0.003^{ns}	0.935^{ns}	9.468*
Gear ×Speed	12	2.388*	0.628*	0.017*	0.0003^{ns}	0.002^{ns}	0.621^{ns}	6.930*
Operation ×Gear ×Speed	12	2.011^{ns}	0.417^{ns}	0.013^{ns}	0.001^{ns}	0.004*	0.398^{ns}	3.248^{ns}
Error	80	1.083	0.249	0.009	0.001	0.002	0.472	3.648
Total	120							

Note: ^{ns} Non significant, ** Significant at p<0.01, * Significant at p<0.05

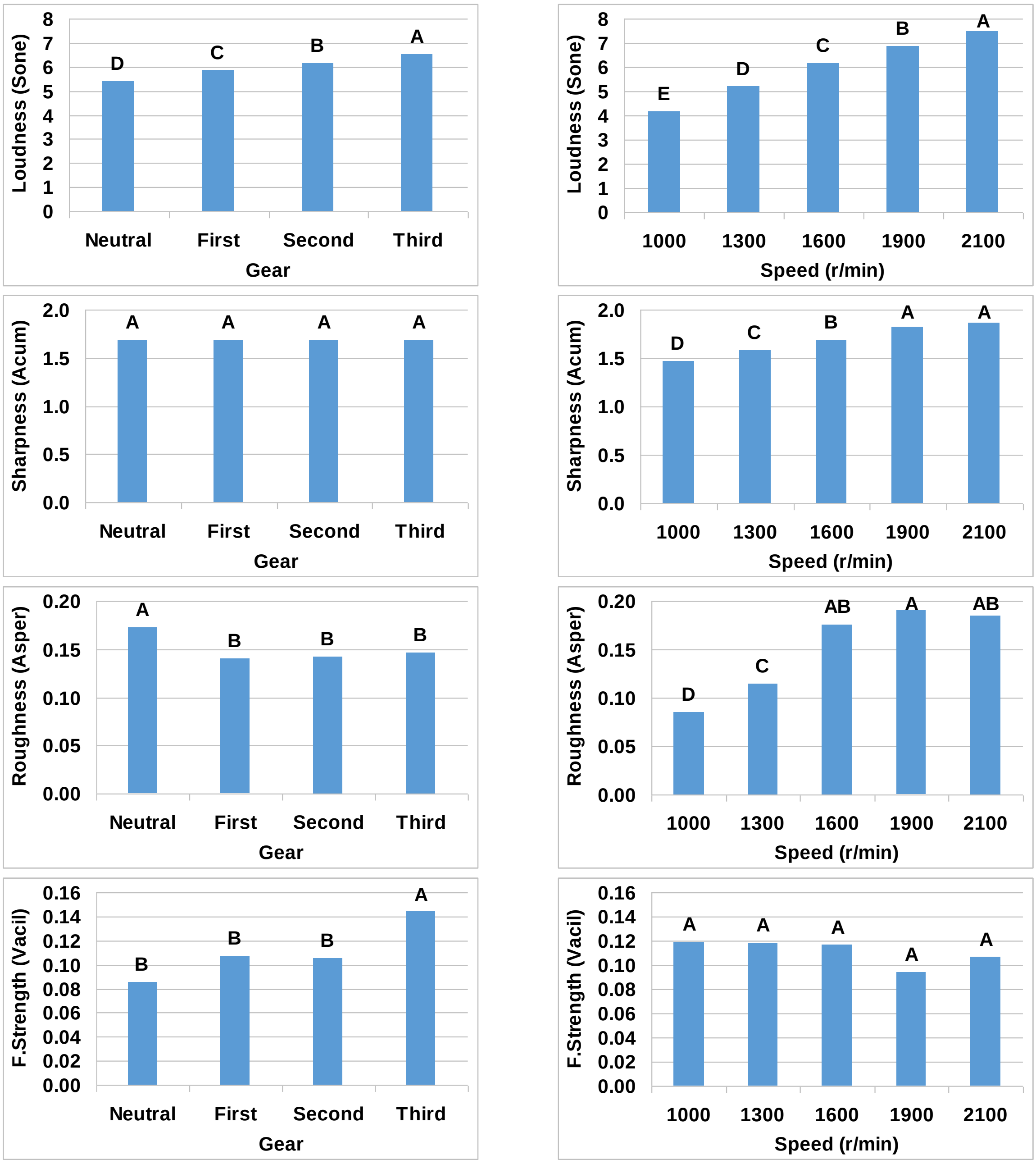

Figure5 Sound quality metrics at different gear ratio and engine speed

Figure 6, Figure 7 and Figure 8 depict L_{Aeq}, PA and UBA with respect to gear ratio and engine speed for two operation types, respectively.

Figure6 L_{Aeq} at different operation type versus gear ratio and engine speed

Figure7 PA at different operation type versus gear ratio and engine speed

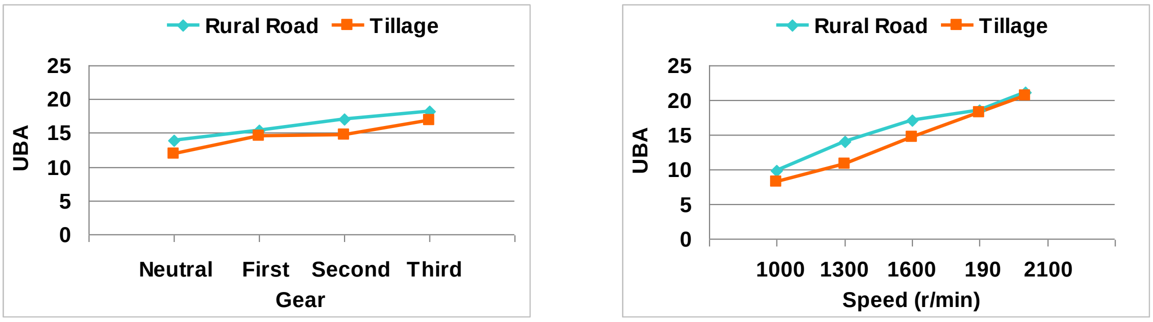

Figure8 UBA at different operation type versus gear ratio and engine speed

L_{Aeq}, PA and UBA versus gear ratio and engine speed showed in Figure 9.

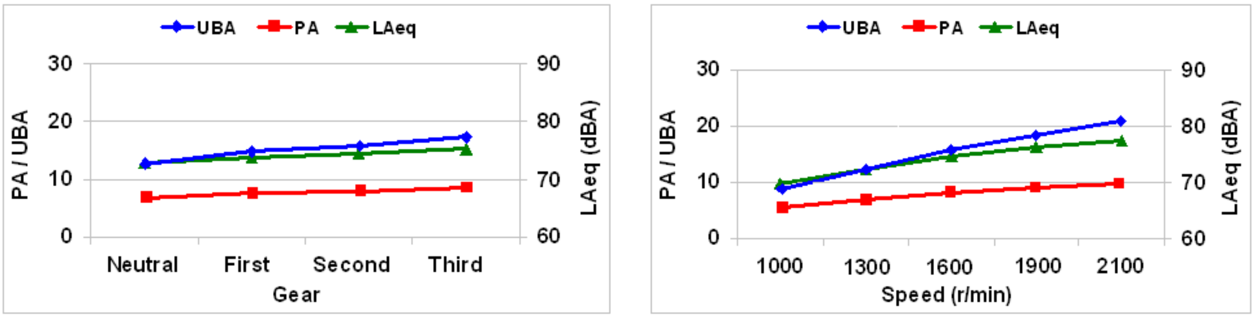

Figure9 L_{Aeq}, PA and UBA versus gear ratio and engine speed

Table 3 shows minimum, maximum values and percentile difference of L_{Aeq}, PA and UBA.

Table 3 Comparison of L_{Aeq}, PA and UBA values

		Min. value	Max. value	Percentile difference
L_{Aeq}	Gear	72.77	75.38	3.6
	Speed	69.73	77.36	10.9
PA	Gear	6.96	8.73	25.4
	Speed	5.41	9.79	80.9
UBA	Gear	12.90	17.55	36.0
	Speed	8.99	20.87	132.1

The relationship between L_{Aeq} values and the corresponding PA and UBA is shown in Figure 10. As a result of regression analysis, it was obtained a regression function (Equation15 and Equation 16).

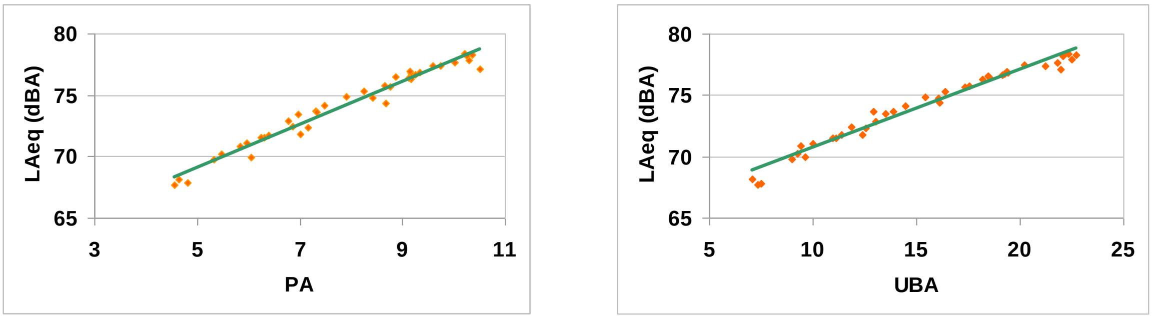

Figure10 Linear regressions of L_{Aeq} values and the corresponding PA and UBA

$$PA = 1.7436\,L_{Aeq} + 60.416 \qquad R^2 = 0.97 \qquad (15)$$

$$UBA = 0.6379\,L_{Aeq} + 64.332 \qquad R^2 = 0.97 \qquad (16)$$

4 Discussions

According to variance analysis with L_{Aeq}, PA and UBA, operation type, gear ratio and engine speed were found to be significant (P< 0.01). As revealed in the Table 2, there is a significant relationship between loudness level and operation type, gear ratio and engine speed (P< 0.01). But, no significant relationship was observed between three other sound quality metrics and one of the sources. Such a result is also can be seen in Figure 5.

As seen in Figure 5, except for loudness that increases with increasing both gear ratio and speed significantly, other metrics do not follow a clear trend. In some cases, the metric increases or decreases, but, the differences between means that are obtained from Duncan's test are not significant.

As revealed in this figure, all of L_{Aeq} for rural road are higher than tillage condition. When plowing, the moldboard plow is placed inside the soil as a fulcrum and the vibration of components can be taken. As a result, the noise caused by the movement of these components decreases. On the other hand, the noise attenuation of track has an important role. This phenomenon is related to the noise attenuation characteristics of different surfaces known as ground effect (Attenborough, 2000). In fact, rural road as a hard surface could reflect airborne noise and propagate toward the operator. Whereas, soft and porous surface such as tilled soil dissipate the noise energy and sound absorption occurred. This is consistent with the findings of Hassan-Beygi and Ghobadian(2005).

According to Figure 6, the L_{Aeq} values rise significantly with increasing gear ratio from neutral to third gear. It should be noted that higher gear selection results in fast forward speed. The speed of the tractor also affects the noise level, due to the increase in tire and track interaction. As a tire rolls over the track, air is forced out of voids or pockets in the track. This rapid exit of air can lead to sound generation. As the tire rolls out of contact, air is rapidly sucked back into the track voids, creating again a rapid displacement of air which can generate sound. Air pumping also occurs when the air is pressed out of the voids in the tire tread pattern (Hanson et al., 2004).

It can also be clearly observed in Figure 6 that increasing engine speed leads to an upward trend in the value of the L_{Aeq}. As expected, sound generation increases when engine speed increases, due to the increasing movement of the reciprocating and rotational parts of the engine. Similar results are reported by other studies (Hassan-Beygi and Ghobadian, 2005; Meyer et al., 1993).Moreover, another reason for this increase may be related to engine exhaust effects due to a higher rotational engine speed (Sathyanarayana and Munjal, 2000).

Both Figure 7 and Figure 8 are also revealed that PA and UBA for rural road are higher than tillage condition. Compared with Figure 6, graphs are actually closer to each other and in fact have fewer differences between them.

According to Figure 9, these three parameters are expected to show similar trending data since they are designed to compensate for the human perception of sound amplitude at various frequencies. Given these similarities, it can be deduced that L_{Aeq} is just as useful tool for induction noise annoyance analysis. In addition, the Figure 9 shows that L_{Aeq}, PA and UBA strongly depend on engine speed rather than forward speed.

According to Table3, the percentile difference of engine speed is 3.0, 3.2 and 3.6 times the percentile difference of gear ratio for L_{Aeq}, PA and UBA, respectively.

Regarding to Figure 10 and Equation 15 and Equation 16, in general, increasing the L_{Aeq} will increase PA and UBA. It was thought that there is a strong correlation between L_{Aeq} and PA and UBA and the coefficient of correlation for both regression model were R^2=0.97. The L_{Aeq}, obtained in this research, will be a good indicator of the PA and UBA.

5 Conclusions

The findings of this study can be summarized as follows:

According to variance analysis with L_{Aeq}, PA and UBA, operation type, gear ratio and engine speed were found to be significant ($P< 0.01$).

There is significant relationship between loudness level and operation type, gear ratio and engine speed ($P< 0.01$). In addition, no significant relationship was observed between sharpness, roughness and fluctuation strength and one of sources.

As a result, except for loudness that significantly increases with increasing both gear ratio and speed, other metrics do not follow a clear trend.

It was seen that L_{Aeq}, PA and UBA for rural road are higher than tillage condition.

As a result of regression analysis, PA and UBA correlated strongly with L_{Aeq} analysis (R^2=0.97).

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