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NOISE MEASUREMENT TECHNIQUES FOR TRACTOR OPERATED MACHINERY

J A Lines and S R Lee
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Measurement of the contribution of noise at a tractor driver's working position from a machine driven by a tractor power take-off shaft is complicated by the need to separate the noise contribution of the machine from that of the tractor. Methods for measuring the noise produced by tractor operated machinery have been compared and evaluated. One of these methods is the acoustic screen technique proposed by Whitaker *et al.* A promising alternative to this method which has been considered is measurement of the noise directly at the driver's ear position.

Use of the acoustic intensity to determine sound power has also been assessed and has been found to be unsuitable for this application.

Situations which could cause errors in noise assessment have been identified and suggestions for the further development of either the acoustic screen method or the driver's ear method have been made. In particular, further consideration is required to establish a method for specifying the type of soil to be used when measuring the noise produced by soil engaging implements. A method for accounting for the change of engine noise due to a change in engine load is also required. These two methods have been used to estimate the total noise of the tractor and the machine at the driver's ear. Measurement of the noise at the driver's ear was found to give slightly more accurate results than the acoustic screen method. In addition, this method is applicable to a wider range of machines and it is simpler to undertake.

It is recommended that consideration be given to the adoption of the driver's ear method for measuring the noise contribution from tractor powered machines.

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Noise measurement techniques for tractor operated machinery

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NOISE MEASUREMENT TECHNIQUES FOR TRACTOR OPERATED MACHINERY

J.A. Lines, S.R. Lee

AFRC Institute of Engineering Research, Wrest Park, Silsoe, Bedford, MK45 4HS

1 Introduction

Workplace noise regulations require the manufacturers, importers or dealers and of agricultural machinery to provide information about the noise generated by their machines. This is to enable employers to determine whether operators of these machines will be exposed to noise levels above either of the defined action levels and if so to determine what action is necessary to protect themselves or their employees from hearing damage.

One way to specify the noise level created by a machine is to measure the sound pressure level at a given point, typically close to the machine operator. An alternative method is to determine the overall sound power produced by the machine. Sound pressure levels at any point can then be predicted by assuming that the sound is propagated equally in all directions.

Determination of the noise levels produced by tractor mounted machines is complicated by noise produced by the tractor which is needed to support the machine, to propel it forward and to provide power. However since the machine may be used with a wide range of different tractors the noise produced by the machine must be measured separately from that of the tractor and be independent of the noise attenuation characteristics of the tractor cab.

Because of the wide diversity of agricultural machines, tractors and agricultural tasks, a precise method for predicting the noise which will be created by a machine in use is impractical. However a measurement method is required that will enable general information about a machine to be provided. This information, together with specific local advice will provide a basis on which noise dose assessments can be made.

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The measurement method should be simple and inexpensive to perform, it should be repeatable at different testing locations using different tractors and it should be representative of the machine in use. Failure to meet any of these three criterion adequately will seriously detract from the usefulness of a procedure.

A test procedure for measuring the noise generated by farm machinery trailed or mounted behind a tractor and powered by the tractor has been proposed for this purpose (Whitaker *et al.* 1985). In this method the noise from a tractor powered machine is recorded close to the rear window of the cab. In order to minimize the cab noise from the tractor and that reflected from rear window of the tractor, the recording microphone is placed in the centre of a 1 metre square board of 19 mm plywood which is covered with 100 mm thick open cell polyurethane foam. This acoustic screen is supported as close as possible to the rear window of the tractor cab, between the window and the machine being tested. The microphone is positioned level with the tractor drivers head. The acoustic screen is isolated from the tractor body by suitable noise isolation mounts. The A weighted noise level at this position is measured with the tractor and machine moving over the ground at the recommended machine operating speed and engine speed but with the machine raised above the crop and the p.t.o. shaft disengaged. This provides an estimate of the tractor noise. The noise level is then measured under the same conditions but with the p.t.o. shaft engaged and the machine working normally. This provides an estimate of the total noise produced by the tractor and machine together. A logarithmic subtraction between the two noise levels is used to determine the sound levels attributable to the machine in work.

This procedure has been reviewed and tested. Specific consideration has been given to ensuring accurate measurement of the noise created by the machine at the acoustic screen, to ensuring that the results are representative of the noise created by the machine in use and to interpreting the noise levels measured at the acoustic screen.

Noise levels at the acoustic screen and at the drivers ear position with cab windows open and close have been measured. Measurements have been made on a range of machines and tractors. In particular three machines with differing noise levels were each measured on a set of three different tractors. The results of the measurements have been used to identify potential sources of error in the noise measurement. The results have also been used to test how well the total noise at the drivers ear can be predicted from separate measurements of the machine and tractor contributions.

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2 Accurate measurement of the noise at the acoustic screen

2.1 Uncertainty due to excessive tractor noise

In principle it is possible to measure very small increases in noise and to infer from this change the noise level of the additional noise source necessary to cause this increase. In practise small errors in the measurement of the two noise levels and small changes in these noise levels between the two measurements occur. If the difference between the two levels is small these changes can result in large errors in the calculated pressure level of the additional noise source. Figure 1 show variations in the noise level produced by a tractor engine measured every 30 seconds over a period of 10 minutes after starting it. The overall variation in noise level was less than 1 dB(A). Such variation can be considered negligible if there is sufficient difference between the tractor noise level and the noise level of the tractor and machine together. However if the difference is small the effect could be significant.

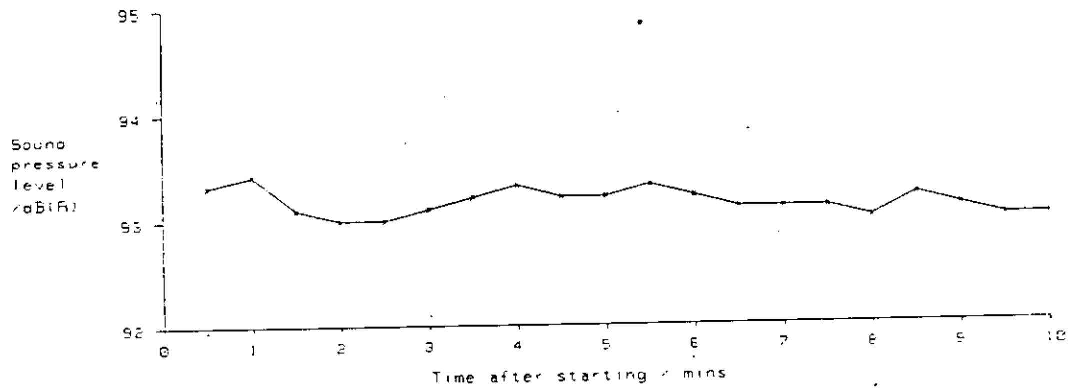

Figure 1: Variations in the measured noise level of tractor engine

An example of this was observed while measuring the noise level produced by a rotary cultivator which was not engaged with the soil. The cultivator was mounted on three different tractors, a Ford 4610, a Ford 6610 and a Massey Fergusson 690. The measurements produced three widely varying estimates of the noise produced by the cultivator ranging from 69.4 dB(A) to 78.3 dB(A). Noise levels produced by a forage harvester and a disc mower also running without crop estimated from

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measurements using the same three tractors showed much greater consistency since the noise levels they produced were greater.

This uncertainty in noise level can be reduced by specifying that the total noise level produced when the machine is driven by the p.t.o. must be at least 3 dB(A) greater than that measured when the machine is not powered. If the increase is smaller than this then a quieter tractor should be sought. If a suitable tractor cannot be found then the noise produced by the machine is unlikely to represent a hazard to the driver. Noise levels measured at the acoustic screen mounted behind the tractors were typically 75 dB(A) (Table 1). Machines producing more than 75 dB(A) would increase the total noise level by the suggested 3 dB(A). Machines producing less than this level are unlikely to contribute significantly to a noise level above either of the action levels.

Table 1 presents the results obtained from this series of measurements. The measured noise levels for each condition are given in the first three columns. The following three columns represent the estimated machine noise contribution at the drivers ear and at the acoustic screen. These result from the logarithmic subtraction of the noise measured with the machine driven from that with the machine undriven. The final two columns refer to predictions of the total noise at the drivers ear position estimated from the various separate estimates of the machine noise and the tractor noise derived in the previous columns. These two columns are discussed further in sections 4.2 and 6.2.

2.2 Error due to variation of engine noise

The proposed measurement method determines the difference between two noise levels measured under different circumstances. It is assumed that the difference between two measurement results is the noise made by the machine. However if there is a change in the tractor noise between these measurements then this change will also be attributed to the machine.

2.2.1 Engine speed

Tractor engine noise variation could arise from variation of the engine speed between the measurement of the tractor noise and that of the total noise. The engine noise of a Massey Fergusson 690 tractor has been measured at different engine speeds. The results are shown in Figure 2. They indicate that the engine noise increases by about 6 dB(A) when the engine speed is doubled.

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Table 1 Results from sample applications of the Acoustic screen measurement method

	Measured dB(A) level at: drivers ear, cab closed	open	acoustic screen	Machine contribution in dB(A) at: drivers ear, cab closed	open	acoustic screen	Error range in estimating total noise in cab using ear position	acoustic screen
Ford 4610 with disc mower								
undriven	81.0	81.4	75.5	72.7	91.8	94.0	-0.1 to 0.9	1.1 to 1.6
driven	81.6	92.2	94.1					
Ford 6610 with disc mower								
undriven	84.0	84.4	76.2	79.8	92.4	94.5	-0.8 to 0.4	0.4 to 1.1
driven	85.4	93.0	94.6					
Massey Fergusson 690 with disc mower								
undriven	77.1	79.9	73.8	77.1	92.8	94.5	-0.9 to 0	0.2 to 0.7
driven	80.1	93.0	94.5					
Ford 4610 with single chop forage harvester								
undriven	80.0	80.7	74.7	74.1	82.3	84.5	0.2 to 1.0	0.7 to 1.2
driven	81.0	84.6	84.9					
Ford 6610 with single chop forage harvester								
undriven	81.4	81.8	75.1	74.4	83.3	84.6	-0.5 to 1.5	0.1 to 1.7
driven	82.2	85.6	85.1					
Massey Fergusson 690 with single chop forage harvester								
undriven	78.4	79.8	74.4	65.1	82.7	84.5	-0.2 to 0.4	0.5 to 0.6
driven	78.6	84.5	84.9					
Ford 4610 with rotary cultivator								
undriven	81.7	81.8	77.1	-	74.2	73.3	-0.9 to 1.0	-1.5 to 0.6
driven	81.6	82.5	78.6					
Ford 6610 with rotary cultivator								
undriven	84.2	84.8	79.6	72.7	91.8	94.0	-3.0 to 0.2	-3.5 to 0.0
driven	84.5	85.5	80.0					
Massey Fergusson 690 with rotary cultivator								
undriven	79.1	79.7	76.1	70.8	78.6	78.2	-1.4 to 0.1	-2.2 to -0.4
driven	79.7	82.2	80.3					

Changes in the engine speed between the two measurements are likely to be determined by the repeatability with which the tractor tachometer can be read and the governor set. This has been tested on the Massey Fergusson tractor. The hand governor of the tractor was set to minimum and then to give an engine speed of 1900 rpm on the tractor tachometer. The setting was made with reasonable care. This was repeated thirteen times. Each time, after the engine speed had been set, the speed was measured with a digital tachometer. Analysis showed that variation in the engine speed had a standard deviation of less than 1% of the mean and that the mean engine speed was

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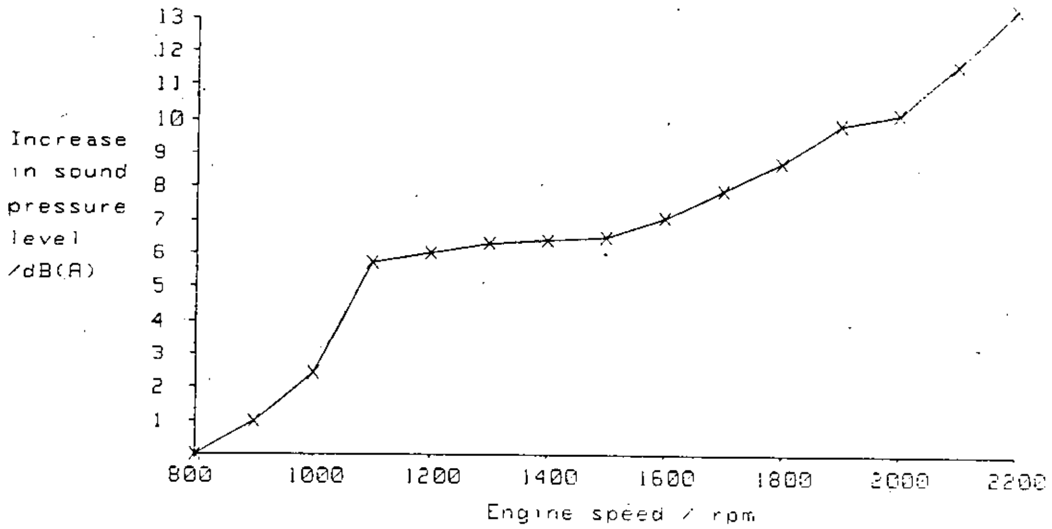

Figure 2: Variation of engine noise level with engine speed. Measurement made behind a stationary **tractor**

only 1% below the nominal speed. Engine speed settings made on this tractor are therefore unlikely to vary by more than about 2%. This variation is likely to cause changes in engine noise of very much less than 1 dB(A). This result suggests that unintentional variation in the engine speed setting between the two measurements of noise level is unlikely to cause a detectable change in engine noise level or to affect the measured machine noise.

2.2.2 Engine loading

The load on a tractor engine is greater when the tractor is supplying power to a machine than when the machine is without power. If a change in engine load affects the noise level produced by the tractor engine then errors will occur in the estimate of the machine noise unless allowance for this change is made.

Engine noise of a Massey Fergusson 690 tractor was measured with different loads on the engine. Noise was measured at the drivers ear and at the acoustic screen. The engine of the was loaded by applying the tractor brakes until the engine speed dropped from 2200 rpm to 1900 rpm. This noise level was then compared with that measured while the tractor was idling at 1900 rpm. The noise level at the acoustic screen when the engine under load was found to be between 6 and 7 dB(A) greater than when the engine was idling at this speed. Noise levels recorded at the tractor drivers ear position with the cab windows open increased by 4 dB(A) when the engine was loaded in this way.

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Measurements of the noise at the tractor drivers ear position have also been made on a John Deere 5420 tractor. At an engine speed of 2200 rpm with the rear window of the cab open a variation of 3.3 dB(A) was recorded between the lightly loaded engine and a heavily loaded engine. With the cab windows and doors closed the total variation was 3.6 dB(A)

Tractor test reports published by OECD (1989) show that the noise level at the drivers ear of a loaded tractor engine can be as much as 7 dB(A) greater than when the engine is running at the same speed under a light load.

Under the proposed measurement method no allowance is made for changes in engine noise due to engine load. Any change in noise which occurs when the p.t.o. shaft is engaged and the machine is processing a crop will be attributed to the machine. This could result in over estimates of the machine noise of quiet machines which require large amounts of power from the tractor engine. A correction table for this error is given in Table 2. Sample use of this table shows, for example, that if the measured noise level at the acoustic screen is 10 dB(A) greater with the tractor and machine than with the machine alone, and if the noise at the acoustic screen of the tractor increases by 7 dB(A) due to the change in load, then the machine noise contribution will be overestimated by 2.6 dB(A) if this change is not taken into account.

Table 2 Error in the estimation of machine noise at the acoustic screen caused by a change in engine noise with load

		Increase in total noise level when p.t.o. shaft is engaged dB(A)																		
		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Increase in tractor noise with load dB(A)	1	2.5	1.3	.8	.6	.4	.3	.2	.2	.1	.1	.1	.1							
	2		3.8	2.1	1.4	.9	.7	.5	.4	.3	.2	.2	.1	.1	.1	.1	.1			
	3			4.7	2.7	1.8	1.2	.9	.7	.5	.4	.3	.2	.2	.1	.1	.1	.1	.1	
	4				5.2	3.1	2.1	1.5	1.1	.8	.6	.5	.4	.3	.2	.2	.1	.1	.1	.1
	5					5.6	3.4	2.3	1.6	1.2	.9	.7	.5	.4	.3	.2	.2	.2	.1	.1
	6						5.9	3.6	2.4	1.7	1.3	1.0	.7	.6	.4	.3	.3	.2	.2	.1
	7							6.1	3.7	<u>2.6</u>	1.8	1.4	1.0	.8	.6	.5	.4	.3	.2	.2
	8								6.3	3.9	2.7	1.9	1.4	1.1	.8	.6	.5	.4	.3	.2
	9									6.4	4.0	2.7	2.0	1.5	1.1	.9	.7	.5	.4	.3
	10										6.5	4.0	2.8	2.0	1.5	1.1	.9	.7	.5	.4
	11											6.6	4.1	2.8	2.1	1.5	1.2	.9	.7	.5
	12												6.6	4.2	2.9	2.1	1.6	1.2	.9	.7
	13													6.7	4.2	2.9	2.1	1.6	1.2	.9
	14														6.7	4.2	2.9	2.1	1.6	1.2

2.2.3 Engine temperature

Another potential reason for the engine noise level to change during the measurement of machine noise is a change in engine temperature. In order to examine this possibility the noise level created by the engine of the Massey Ferguson 690 was measured every 30 seconds for 10 minutes as it warmed up after a cold start. The results show no significant trend in the noise levels. It can be concluded from this that the changes in engine temperature likely to occur between the two comparative measurements are unlikely to be large enough to affect the results (Figure 1).

2.3 Other sources of noise

2.3.1 Noise from the unpowered machine

Error in the estimate of the noise created by a machine can arise due to the noise that the machine makes as it is moved by the tractor without being powered. An example of this was found in a forage harvester. As this forage harvester was towed behind a tractor the pickup mechanism frequently contacted the bodywork of the harvester. The sound caused by this added almost 1 dB(A) to the noise level of the tractor measured at the acoustic screen. If measurement of the machine noise were made according to the proposed method then this noise would be attributed to the tractor, since it occurred when the forage harvester was not powered.

A solution to this could be to amend the procedure specifying that the reference measurement is made driving the tractor without it being hitched to a machine. For some machines which have complicated hitching arrangements, this could make the measurement much more protracted and would allow time for other conditions to change which could also give rise to errors. In such circumstances this problem could be minimised in other ways such as by immobilising the part causing the noise.

2.3.2 Interaction of tractor noise with the machine

Reflection and radiation of the tractor noise from the machine being towed can increase the noise level measured at the acoustic screen significantly. The microphone is especially sensitive to such noises since it is shielded from the noise originating in front of the acoustic screen. To illustrate this the noise at the acoustic screen was measured with and without a trailer mounted tank behind the tractor. The presence of the tank increased the noise measured at the acoustic screen by 3 dB(A) due to reflection of the tractor noise.

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Examination of Table 1 shows that the tractor noise measured at the acoustic screen when the Ford 4610, Ford 6610 and the Massey Fergusson 690 tractors were attached to a rotary cultivator was about 2 dB(A) greater than when they were attached to either the mower or the forage harvester. This change is probably due to radiation of the tractor noise by the rotary cultivator hood. This problem is likely to arise in other machines which are closely mounted to the tractor, carried on the three point linkage and have large panels which can radiate sound efficiently.

Such noise is a result of the interaction of tractor and machine so it can not be ascribed to either alone. It could however affect the noise dose received by the tractor driver so allowance should be made for it.

3 Creating conditions representative of the machine at work

It is important that the machine noise measured is representative of the noise that the machine will make when in use. Factors which could affect the noise made by a machine in use are the crop or soil which it is engaging, the task it is performing, and the state of repair of the machine.

3.1 Crop

The noise made by most machines depends on whether it is running with or without a crop or soil. Some machines such as rotary harrows and some rotovators produce higher noise levels when engaged with the soil than when running suspended above the ground. Other machines such as straw choppers, forage harvesters and root crop lifters have been observed to produce less noise when engaged with a crop than when running empty. In order to ensure that the measured noise level is representative of the machine in work a crop should be used whenever possible.

The noise produced by soil engaging implements could cause measurements of machine noise to vary from test to test. The most obvious example of this is a rotary cultivator where the presence of stones or clods in the soil can increase substantially the noise produced. Some form of standard is required describing the sort of soil which is acceptable for these tests. Results from such tests would need to be accompanied by advice regarding the likely variation of noise levels under different soil conditions.

3.2 Machine operation cycles

Some machines are cyclic in their operation. An example of this is a large bailer. During the pickup phase the noise level created by a round bailer was found to be about 3 dB(A) lower than during the tying phase of the cycle. The proposed measurement method suggests that the maximum noise level should be measured. A more realistic estimate of the machine noise could be obtained by measuring the noise over a whole operational cycle and quoting the energy average level or L_{eq}.

3.3 Machine condition

Consideration of the state of repair of the machine is beyond the scope of this test proposal, focused as it is on new machines. However it is evident that poor maintenance, loose parts and unlubricated bearings could significantly affect the noise produced by a machine.

4 Interpretation of the noise levels

The objective of the test method being considered is to produce information which can be used to assess the noise levels likely to occur inside a tractor cab. Such an assessment will require a knowledge of the machine noise, the tractor noise, and the attenuation of noise transmitted into the tractor cab. The attenuation of airborne noise into cabs of various tractors has been measured with the rear window open and closed. This information provides an indication of the likely variation in machine noise reaching the tractor operator. The noise levels at the tractor drivers ear have also been measured for some machines and the results compared with those results obtained using the acoustic screen technique.

4.1 Attenuation of airborne noise in the cab

The attenuation of white noise from a source placed directly behind the tractor cab was measured for eight different tractors. The noise source was placed 1.5 m above the ground and 2 m from the rear hitch point of the tractor. This position was considered to be representative of some tractor powered machines. Measurements of the noise level inside the cab were made with the tractor parked in a grass field with the engine off. The distance from the noise source to the operators ear position was measured and from this the noise level to be expected at that point in the absence of a

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Table 3 Attenuation of airborne noise into the cabs of various tractors

Tractor	Age	Distance to ear	No cab Level	Closed cab Level	Closed cab Attenuation	Open cab Level	Open cab Attenuation
	(years)	(m)	dB(A)	dB(A)	dB(A)	dB(A)	dB(A)
International 574	15	2.21	77.1	62.4	14.7	77.7	-0.6
Ford 8700	12	3.10	74.2	53.1	21.1	72.2	2.0
County 1174	11	2.92	74.7	55.0	19.7	73.6	1.1
Ford 6600	11	2.58	75.8	56.2	19.6	74.2	1.6
International 1241	10	2.87	74.9	55.5	19.4	73.7	1.2
Ford 4610	8	2.33	76.7	55.3	21.4	74.7	2.0
Massey Fergusson 675	5	2.65	75.5	52.7	22.8	77.0	-1.5
Massey Fergusson 390	1	2.94	74.6	46.1	28.1	71.9	2.7
Massey Fergusson 3090	<1	3.20	73.9	45.1	28.8	74.2	-0.3

cab was calculated. This level was compared with the level measured in the tractor cab with the rear window of the cab both open and with the rear window closed.

With the rear window open, over the range of tractors tested there was a mean decrease in the noise level of 0.9 dB(A) with a standard deviation 1.4 dB(A) compared with the level which would have been expected at that point in the absence of a cab. This reduction has been approximated to 1 dB(A) in the following section. With the cab window closed there was a mean reduction of noise level by 21.7 dB(A) with a standard deviation 4.4 dB(A) (Table 3).

Talamo *et al* (1984) found that for almost 50% of tractor use the rear window of tractor cabs was open. The large difference shown in Table 3 between the attenuation of airborne noise into a closed cab and into one with open windows indicates that for many tractor drivers the overall noise dose received is due mostly to operating the tractor with the windows open.

These results also indicate that the cabs of newer tractors attenuated airborne noise more than those of older tractors. This is probably due to improvement in cab design. The noise attenuation of cabs with the rear window open showed no such trend with tractor age.

4.2 Noise at drivers ear

Measurements of the noise level at the tractor drivers ear have been made for a range of tractors and machines. Measurements were made both with the cab rear window open and with all the cab windows and doors closed (Tables 1 and 4).

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Table 4 Acoustic screen and drivers ear measurements of machine noise using Case 1056 Tractor

	Measured level in dB(A) at: drivers ear cab closed	open	acoustic screen	Machine contribution in dB(A) at: drivers ear cab closed	open	acoustic screen
Case 1056 XL with Kidd bale chopper (p.t.o. speed 540 rpm)						
undriven	-	76.4	78.3	-	84.5	86.9
driven	-	85.1	87.5			
Case 1056 XL with Kidd bale chopper (p.t.o. speed 1000 rpm)						
undriven	-	76.4	78.3	-	92.6	96.5
driven	-	92.7	96.6			
Case 1056 XL with Kidd Sideflinger 650 rotary spreader						
undriven	-	76.4	78.3	-	82.6	84.7
driven	77.8	83.5	85.6			

The noise level expected at the drivers ear for each of the tractor and machine combinations given in Table 1 has been calculated. This calculation was made by taking an estimate of the machine noise from acoustic screen results, reducing it by 1 dB, to account for the attenuation of noise into an open cab, and adding it to the noise level recorded in the tractor at the drivers ear when no machine was being driven. The resulting noise estimate was compared with the measured noise at the drivers ear with the machine working and the difference between these levels calculated. For each tractor given in Table 1 there are three different estimates of the tractor noise level (one with each machine attached but not driven). There are also three estimates of the machine noise contribution of the acoustic screen (one made on each tractor). All combinations of these data have been used to examine variation in the estimates of noise at the drivers ear which could be made. These various estimates have been subtracted from the noise level measured at the drivers ear with the machine working. The maximum and minimum errors in the total noise estimate obtained in this way are given in the last column of Table 1. Estimates of noise at the drivers ear were in error by up to 1.7 dB(A). (Results from the rotary cultivator have been ignored since less than 3 dB(A) difference in noise level was observed between the undriven and driven conditions)

Noise levels at the drivers ear were not calculated for the condition where the cab windows were closed because of high attenuation coefficients of closed cabs. For none of the measurements made under this condition did the noise due to the machine exceed 80 dB(A) at the drivers ear. Calculation

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of noise in the cab in this condition is therefore not likely to be a very important part of an overall noise dose assessment. If such a calculation were considered necessary then the attenuation of the closed cab to airborne noise would be required. This figure cannot be obtained simply from comparisons of cab noise levels with windows open and closed as given in OECD (1988) and EEC (1977) test results since much of the cab noise is structure-borne noise and so is not reduced by closing cab windows.

5 General discussion of the acoustic screen technique

Few problems have been encountered regarding the construction and use of the acoustic screen. It can easily and quickly be fitted onto almost any conventional tractor, the requirement that the microphone be no more than 200 mm from the rear window of the tractor cab was usually achievable.

The acoustic screen is placed directly between the main sources of tractor noise and the microphone. Therefore it reduces the tractor noise sensed by the microphone. The screen is also mounted on acoustic isolation mounts to minimize the solid born noise transmitted into it. Measurements on various tractors indicates that the reduction in total tractor noise at this position caused by the screen is between 4 and 9 dB(A). This reduction facilitates the measurement of quieter machines by increasing the signal to noise ratio of the measurement. It also reduces the effect which a change of tractor noise between the two comparison conditions would have on the noise attributed to the machine.

The acoustic screen also reduces reflections of the machine noise from the rear window of the tractor cab. Without the acoustic screen the noise which would be attributed to the machine at the same point would be almost about 3 dB(A) higher than with the acoustic screen due to these reflections.

The machine noise measured at the acoustic screen is dependant on the thickness of foam covering the board. Measurements suggest that if the thickness of the foam is reduced from 100 mm to 50 mm then the measured levels of machine noise increase by about 3 dB(A).

5.1 Use of the acoustic screen with machines which are not rear mounted

Most of the machines used on tractors are rear mounted. This is therefore the most important class to be considered for this method. It is also the group of machines for which the acoustic screen method is best designed. Side mounted and to some extent front mounted machines also present a potential noise hazard to the operator. In particular Talamo *et al* have identified side mounted hedge cutters as presenting a hazard. An acoustic screen mounted on the side of a cab oriented towards a side mounted machine will not attenuate the tractor noise as effectively as a rear mounted acoustic screen since it is no longer directly between the tractor noise sources and the microphone. More difficulty will therefore be experienced in accurately measuring the noise created by the machine.

An additional problem occurs with machines which have two or more sources of noise which are located at different points relative to the cab. Side mounted hedge cutters usually have a hydraulic pump at the rear of the tractor to drive the cutting head, and the cutting head at the side of the tractor. Because of the separation of noise sources it is not possible to measure the noise of such a machine using the acoustic screen technique.

6 Alternatives to the acoustic screen

In order to overcome some of the limitations of the acoustic screen method for measuring machine noise, two other techniques have been investigated.

6.1 Sound power

The total sound power emitted by a machine can be measured by integrating the sound levels measured or estimating at all points over a surface which completely surrounds the object creating the noise. Once the sound power produced by an object is known the sound pressure level at any point can be estimated from this by assuming that the sound field is isotropic. A method exists which enables the sound power created by an object to be measured in the presence of other noise. This technique relies on measuring the acoustic intensity or the flow of sound rather than the sound pressure.

An imaginary boundary is created which completely surrounds the source of noise which is to be measured and which excludes all the sources of noise which are to be ignored. By measuring the acoustic intensity at all points on this boundary the total sound power emerging from the source can be calculated. The flow of sound from external sources will be measured entering the boundary on one side of the source and flowing out again on the other side so its effect is negated.

Such a technique might seem an ideal method for measuring the noise created by a tractor powered machine, however there are several reasons relating both to the principles and practise of this technique and the use of sound power in general which make it unsuitable for use in this situation.

In order to calculate the sound pressure level at a point from the sound power of a source the sound field created must be assumed to be isotropic. The sound is also assumed to originate from a known point source. Neither of these assumptions can be made for most agricultural machines. The noise created is frequently directional and there is often more than one source of noise on a machine.

Acoustic intensity measurements measure the flow of sound by detecting the small phase lag which exists between two microphones which are spaced a known distance apart. The accuracy of this measurement is therefore greatly reduced in sound fields where the sound pressure level is high but where there is little overall flow of sound. Such a field frequently exists between a closely mounted machine and the back of a tractor since they both reflect sound efficiently. A reliable measurement of the sound power of a machine close to a tractor cannot be made for many machines.

Measurement of the sound power requires measurements to be made at many locations all around a noise source. For a stationary machine which this is usually achieved by holding the acoustic intensity head at predetermined points or scanning it smoothly over a surface. With a moving machine it is too dangerous for an operator to walk in front of the machine making these measurements, so a large number of measurements at fixed microphone locations becomes necessary. This procedure would then be very costly and time consuming.

The above reasons combined with the high cost of the equipment necessary to measure acoustic intensity renders its use for machine noise measurement impractical except by specialised test stations.

6.2 Measurement of machine noise at the drivers ear

Measurements of the noise produced by a machine can be made at the drivers ear by comparing the total noise level of the tractor and machine with that produced by the tractor alone in the same way as is done using the acoustic screen technique. Measurements must be made with the cab windows open otherwise the change in noise level is likely to be too small to measure reliably. This method is more general in its application than the acoustic screen method since it is equally applicable to machines mounted at the rear, the side or the front of the tractor, with single or multiple noise sources.

Measurement of the machine noise contribution at the drivers ear produces similar information to that produced by the acoustic screen measurements. The main difference between the results is that measurements at the drivers ear include the noise attenuation of the tractor cab on which the measurement was made whereas the acoustic screen results do not. However in interpreting the results of the acoustic screen measurements information is required regarding the attenuation of the machine noise into the cab. If such information is made available then it could also be used to correct the machine noise levels calculated using measurements at the drivers ear.

Table 3 indicates that the attenuation of machine noise into the tractor cab varies between tractors by only a few dB(A) so it might be considered acceptable to assume an average value for all tractors. If such an assumption is made then the error in noise dose assessment introduced by this assumption could be a little larger for results gained from measurements at the drivers ear than for results gained from the acoustic screen. However since the noise attenuation of an open cab can be expected to vary with the position of the noise source relative to the open window, errors in the calculation of driver noise dose resulting from differences in position would be reduced by the use of the drivers ear position method.

The noise level at the drivers ear has been calculated from data presented in Table 1. For each combination of tractor and machine the noise level due to the tractor at the drivers ear has been taken from measurements made with the tractor attached to, but not driving one of the other two machines. The machine noise contribution has been taken from the measurements made on one of the other tractors. These two levels have been added together and compared with the noise level measured when the tractor was driving the machine. For each tractor and machine combination, various combinations of these figures give four estimates of the noise level. These have been calculated and compared with the measured level. The range of differences is given in the penultimate column of Table 1. Only four estimates have been made in order to avoid the situation where a noise level measurement which contributes to the estimate is also the level with which the estimate is compared. The errors in the estimate of the noise at the drivers ear are smaller using this method than from comparable measurements using the acoustic screen, also given in Table 1. This suggests that in practice measurement at the drivers ear could be a more accurate method of determining machine noise than measurement at the acoustic screen.

If the airborne noise attenuation coefficient of closed cabs was made available, then the difference between this and the attenuation coefficient of the open cab could be used to estimate the noise contribution of a machine into a closed cab.

7 Conclusions

The acoustic screen technique is an easy and practical method for measuring the noise created by rear mounted machines. It is likely to be a less effective method for measuring the noise of side mounted machines and is impractical for measuring the noise of machines with noise sources which are distributed around the tractor.

An alternative measurement method which should be given consideration is measurement of the machine noise contribution at the drivers ear. This method is similar to the acoustic screen method in that it is based on comparisons of the noise level with and without the machine being operated. It is simpler to carry out than the acoustic screen, evidence suggests that it is a more accurate method and it is applicable to all types of machine.

Acoustic intensity methods for determining the sound power and hence the noise contribution of the machine are impractical.

7.1 Further requirements to improve measurement accuracy

Regardless of whether the acoustic screen or the drivers ear method is used, the following points require further attention:

(i) A method is required for determining the likely change in tractor noise due to engine load, between the lightly loaded condition when the p.t.o. shaft is not engaged, and when it is engaged.

(ii) A description is required of the range of soil types which would be acceptable for use when the noise contribution of soil engaging implements such as rotary cultivators or rotary harrows are used.

(iii) If it is considered necessary to estimate the noise contribution of a machine inside a closed cab then data for each tractor regarding the attenuation of airborne noise into the cab should be made available by the tractor manufacturers.

(iv) The measurement of the average noise level over the operating cycle should be made for machines which have cyclic changes in noise levels.

(v) Measures should be taken to avoid measuring the transport noise created by the machine when it is not being driven by the tractor. This could include disconnecting the machine from the tractor during measurement of the tractor noise alone.

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