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Whole-body vibration: Initial evaluation of emissions originating from modern agricultural tractors

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Whole-body vibration: Initial evaluation of emissions originating from modern agricultural tractors

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An initial study was conducted to quantify whole-body vibration (WBV) emissions levels found upon a limited range of modern agricultural tractors (5 examples), when operated in controlled conditions (traversing ISO ride vibration test tracks). Vibration emission levels were found to increase with travel speed and surface roughness , but reduce as vehicle size (mass) increased. The presence of vehicle (cab and/or front axle) suspension systems also served to reduce the degree of vibration increase with travel speed. Under standard test conditions, the highest single-axis vibration emission magnitude (for all the tractors tested) was within the range 0.8 - 1.5 m/s^2. However, application of the 1.4 multiplication factor (as required by ISO 2631:1997), increased this range to 1.2 - 2.0 m/s^2: considerably in excess of the WBV exposure limit value (ELV) proposed by the EU Physical Agents (Vibration) Directive (PA(V)D). If the vibration emission values encountered in this study were to be endured by a tractor operator for 8 hours in a day, the proposed ELV would be exceeded. However, it is not known (at this stage) if tractors exhibiting these vibration emission values will expose their drivers to daily averaged vibration exposure levels that would exceed the PA(V)D limit (ELV). Further investigation is required to establish linkage between the test track WBV emissions characteristics of given vehicles, and subsequent WBV emissions and operator daily WBV exposures encountered during typical agricultural operations. It would be desirable to attempt short-term delay of the proposed EU PA(V)D until the findings of such an investigation (which is currently underway) become available.

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WHOLE-BODY VIBRATION: INITIAL EVALUATION OF EMISSIONS ORIGINATING FROM MODERN AGRICULTURAL TRACTORS

1. OBJECTIVE

The objective of this work was to undertake a Pilot research study to quantify Whole-Body Vibration (WBV) emissions levels found upon a limited range of modern agricultural tractors, operating in controlled conditions. The resulting information was to be made available within a short timescale, to aid HSE and vehicle manufacturer input to discussion of the Physical Agents (Vibration) Directive 2000 by the European Parliament.

2. INTRODUCTION

Previous studies[1, 2] have shown that agricultural vehicle operators are exposed to high levels of whole-body vibration (WBV). Recent developments in agricultural vehicle design have resulted in the introduction of cab and axle suspension systems by manufacturers, in addition to (or in place of) the well-established use of suspended seats. Legislation currently under development within the European Union (Physical Agents (Vibration) Directive (2000)), will potentially limit the WBV daily exposure levels of vehicle operators, thereby potentially necessitating changes to agricultural vehicle usage patterns at a time when the farming industry is under severe economic pressure. It is therefore in the interest of employers, vehicle manufacturers and the HSE to ensure that the proposed legislation is both adequate (in terms of operator protection) and realistic (in terms of practical implementation).

A larger, subsequent investigation (12 months duration) is proposed:-

i) to establish the WBV levels that may currently be found upon modern agricultural vehicles, both when traversing artificial ISO ride vibration test tracks **and** during a range of typical field operations;

ii) to consider the consequences of prescribing WBV operator exposure level limitations upon agricultural vehicle usage patterns;

However, initial information is required now to enable informed lobbying during the political development of the proposed legislation. The current investigation attempts to provide this initial information within the limited timescale available, and complement the anticipated main investigation.

Silsoe Research Institute (formerly NIAE) has a long, successful record of applied research in the area of agricultural vehicle ride vibration, originating from the mid-1960's[3], and described in some detail by Lines and Stayner (1999)[4]. Early work identified the need for standardised testing surfaces (and associated testing procedures) to enable investigation of tractor suspension seat performance and vehicle ride vibration characteristics. Two test surfaces, representing a 100 m section of an un-metalled farm roadway and a 35 m long diagonal path across a ploughed field, were defined and reconstructed as artificial test surfaces at NIAE (see Figures 2 & 3). These were subsequently incorporated (and defined) within the

ISO 5008[5] test standard, and the EC Directive for suspension seat evaluation (78/764/EEC)[6], and have since been utilised in much subsequent agricultural tractor ride vibration research, both within Europe and elsewhere. The NIAE pursued a comprehensive programme of research into tractor ride and methods for its improvement, including field studies of vibration magnitude[1], simulation of ride dynamics[7, 8], practical developments[9, 10, 11, 12], and subjective studies including the postural support provided by tractor seats[13]. In the course of these studies, staff of NIAE (and now Silsoe Research Institute) gained a thorough grounding in the human effects of whole-body vibration, which has been followed up to the present (Stayner, 2001)[14].

3. METHODOLOGY

3.1 TEST VEHICLES

A number of factors can affect the level of whole-body vibration experienced by a vehicle operator, when driving over a given surface at a given speed. These include the presence of certain 'ride comfort' features on the vehicle, such as suspended axle(s), suspended cab, and the type/complexity of suspension seat fitted. However, basic properties such as vehicle mass, wheelbase, tyre size, tyre stiffness and inflation pressure can also play contributory roles. For this reason, at the request of the participating manufacturers, a range of agricultural tractors was included within this limited investigation, to determine if whole-body vibration levels experienced upon popular, smaller vehicles (less than 70 kW engine power) would both exceed levels found upon larger, more complex tractors (possibly incorporating 'ride comfort'-enhancing features), and exceed exposure limit values (ELV) being discussed in the European Union. To this end the following range of agricultural tractors was kindly provided for the purposes of the investigation (see Table 1 and Figure 1):-

Table 1
Test vehicles used in the investigation

Tractor model	Engine power (kW)	Mass (kg)	Wheelbase (m)	Suspension features (in addition to the seat)
John Deere 5300	40	2692	2.114	None
Massey Ferguson 4255	71	3778	2.350	None
New Holland TS115	75	4616	2.623	None
Renault Ares 620 RZ	81	4988	2.750	Fully-suspended cab
New Holland TM165	120	6518	2.787	Front axle suspension - Cab suspended rear only

All vehicles tested were four-wheel-drive models: all were fitted with parallelogram-type suspension seats embodying mechanical spring and damper suspension systems, with the exception of the New Holland TS115 & TM165, whose seats incorporated air suspension systems (see Appendix 1). The seats fitted to the New Holland TS115, TM165 and Renault 620RZ also embodied limited longitudinal (y - axis) suspension movement.

Figure 1
Vehicles used in the investigation

The vehicles were considered to represent a substantial proportion of the tractor types originating from UK manufacturing sites, but it is accepted that in order to consider current UK market breakdown more completely, larger (higher engine power) and fully suspended vehicles will require inclusion within the 12 month duration investigation.

3.2 TEST CONDITIONS

Levels of whole-body vibration, to which the operator is likely to be exposed, were measured on five selected agricultural tractors (see Table 1 and Figure 1), in accordance with an extended version of the methodology described within ISO 5008[5]. Each vehicle was driven over examples of ISO 100 m (smooth) and ISO 35 m (rough) artificial test tracks (see Figures 2 & 3 respectively), at a range of constant forward speeds (see below). During each pass across the tracks, vibration levels were measured in three mutually perpendicular directions (x - transverse, y - longitudinal, z - vertical), both upon the surface of the operator's seat and upon the vehicle cab floor, close to the seat mounting.

The ISO 5008[5] test methodology was extended in this instance, in terms of the ranges (and increments) of vehicle forward speed used upon each test track. ISO 5008[5] currently recommends forward speeds of 10, 12 & 14 km/h for the smooth track, and 4, 5 and 7 km/h for the rough track. Whilst the rough track speeds were considered sufficiently high even for larger vehicles embodying some suspension features, the smooth track speeds were considered inadequate, being both too low for some of the vehicles tested and of insufficient increment to ensure correct identification of the point(s) in the vehicle's forward speed range, at which its ride vibration behaviour is likely to exhibit non-linear tendencies (usually between 12 & 16 km/h). To overcome these difficulties the following vehicle forward speeds were used on the tracks, the maximum forward speed on the smooth track being selected according to operator discretion (daring & discomfort threshold). Three test replicates were performed at each of the ISO 5008[5] test speeds, one replicate at all others; in order to maintain the test programme within reasonable limits.

Figure 2
ISO 100 m (smooth) track

Figure 3
ISO 35 m (rough) track

Vehicle test forward speeds were:-

ISO 100 m (Smooth) Track :- 10, 12, 13, 14, 15, 16, 18, 20, 24 & 30 km/h.

ISO 35 m (Rough) Track:- 4, 5, 6 & 7 km/h.

All (operator-removable) additional ballast weights were removed from the test vehicles prior to testing. Wherever possible, tyre pressure levels were set to manufacturers recommended levels for the unladen axle loadings exhibited by the vehicles, but in many instances a combination of large tyre sizes and low axle weights made this impossible. In such instances tyre pressures were reduced to the lowest levels recommended for 30 km/h operation for the given tyre size. Tyre pressures were re-adjusted following initial vehicle 'warm-up' travel on the Silsoe Research Institute (SRI) OECD test track, prior to vehicle WBV emission measurement. Test vehicle spring suspension seats were adjusted in accordance with the instructions provided in the operator's handbook; adjustable damper features were set to mid-range position. Where seat designs embodied longitudinal (y - axis) suspension movement (New Holland TS115 & TM165, Renault Ares 620 RZ), this feature was used. Full details of both test vehicle specifications and setup are given in Appendix 1.

3.3 INSTRUMENTATION

As mentioned previously, vibration levels were measured simultaneously in three mutually-perpendicular directions (x - transverse, y - longitudinal, z - vertical), at two locations on each tractor, as each vehicle traversed an ISO track at a given travel speed (see Section 3.2). Tri-axial vibration present on the cab floor, close to the seat mounting point, was measured using an array of three mutually-perpendicular piezoresistive accelerometers with integral signal conditioning (IC Sensors *type* 3140-005)). Tri-axial vibration on the drivers's seat was measured by placing a semi-rigid mounting disc, incorporating three mutually-perpendicular piezoelectric accelerometers (Bruel & Kjaer *type* 4322), on the seat cushion, approximately between the driver's ischial tuberosities (vertically below the Seat Index Point).

Accelerometer outputs were acquired by a ruggedized laptop Personal Computer-based signal conditioning, data acquisition and analysis system, *HVLab* (*version* 3.81). (This system was developed by the Institute of Sound and Vibration Research, University of Southampton, for acquiring and analysis time-varying signals). Silsoe Research Institute's *HVLab* system incorporates signal conditioning circuitry to enable direct interface with piezoresistive or strain gauge-based transducers: a Larson Davis Human Vibration Meter *type HVM100* was used to convert and amplify the output of the piezoelectric seat pad accelerometers into proportional voltage form, prior to signal acquisition. The acceleration waveforms were low-pass filtered at 100 Hz, via integral anti-aliasing filters in the *HVLab* system, and then digitised at 300 samples/second. An additional channel of the *HVLab* system was used to record pulses indicating the start (front wheel on track) and stop (front wheel off track) points, resulting from an in-cab push-button operated by the tractor driver. The data resulting from each track pass was visually inspected for abnormalities prior to recording to file.

3.4 DATA ANALYSIS

During the process of data analysis, it was initially necessary to extract the sections of the acceleration time-histories which corresponded solely to travel upon the ISO tracks; i.e. to eliminate the run-up and run-off periods. These sections were extracted from the acceleration-time data by use of the driver-instigated start and stop indication pulses acquired during each test, and also checked visually for abnormalities. The acceleration records were then normalized (to remove any remaining zero offsets) and frequency weighted, using the weighting factors w_d and w_k specified in ISO 2631 (1997)[15], for the horizontal and vertical axes respectively, before calculation of root mean square (rms) acceleration values. Combined three-axis acceleration values were obtained for both cab floor and driver's seat by calculating the root of the sum of squares (RSS) of each axis component, and also for the seat position when each of the horizontal axes components were first multiplied by 1.4 (see Section 4).

4. RESULTS

Three sets of graphical results are presented for each tractor tested, with the exception of the MF 4255, (see Figures 5, 6, 8,11 & 12). These graphs depict frequency-weighted rms acceleration levels recorded at the cab floor and driver's seat, plotted against vehicle forward speed, for travel across the ISO 35 m and ISO 100 m test tracks. Two sets of seat acceleration graphs are shown per tractor, one being the frequency weighted rms values "as measured", the other having been derived by application of a factor of 1.4 ("1.4 multiplier") to both horizontal (x & y axis) acceleration components (as required for vibration emission declaration, e.g. ISO 5008[5]). Tabular data is presented in Appendix 2.

Figure 4
John Deere 5300 tractor

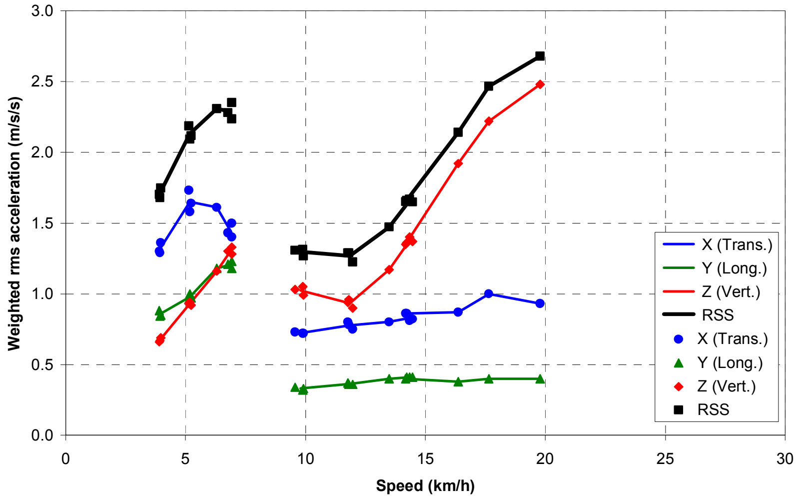

Figure 5.1: John Deere 5300 floor acceleration

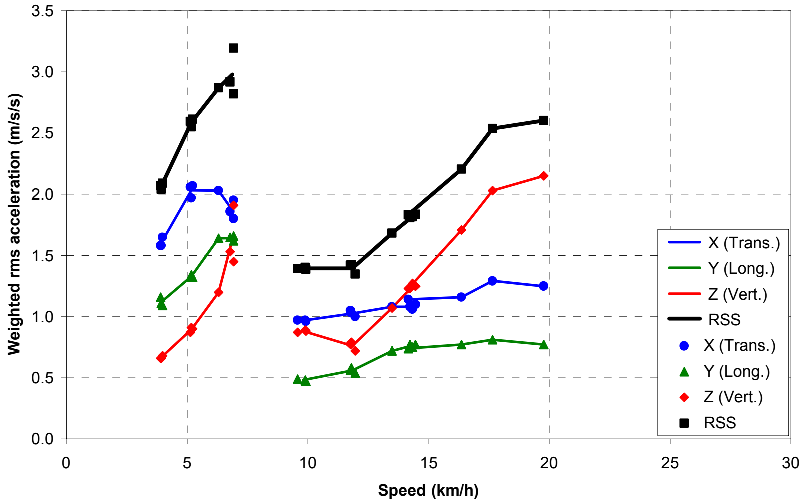

Figure 5.2: John Deere 5300 seat acceleration

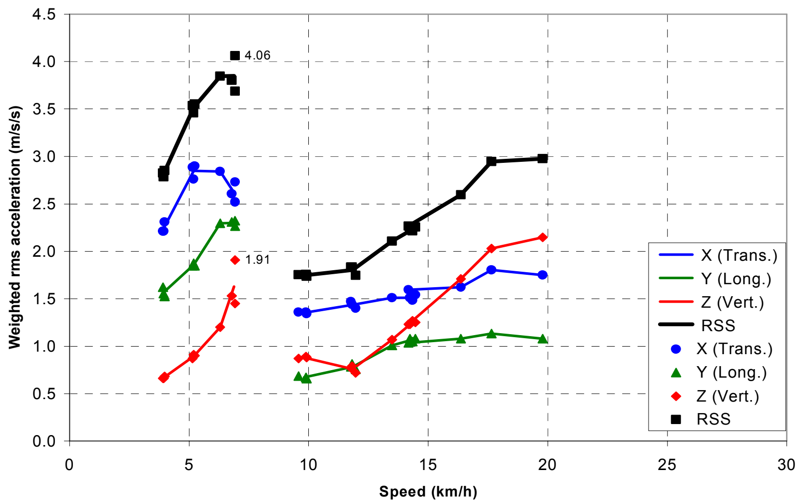

Figure 5.3: John Deere 5300 seat acceleration (*1.4 multiplier*)

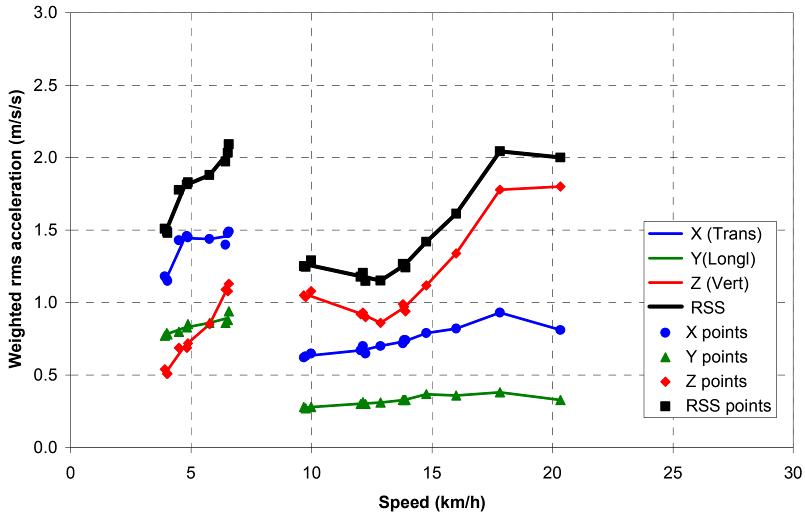

Figure 6: Massey Ferguson 4255 floor acceleration

Figure 7
Massey Ferguson 4255 tractor

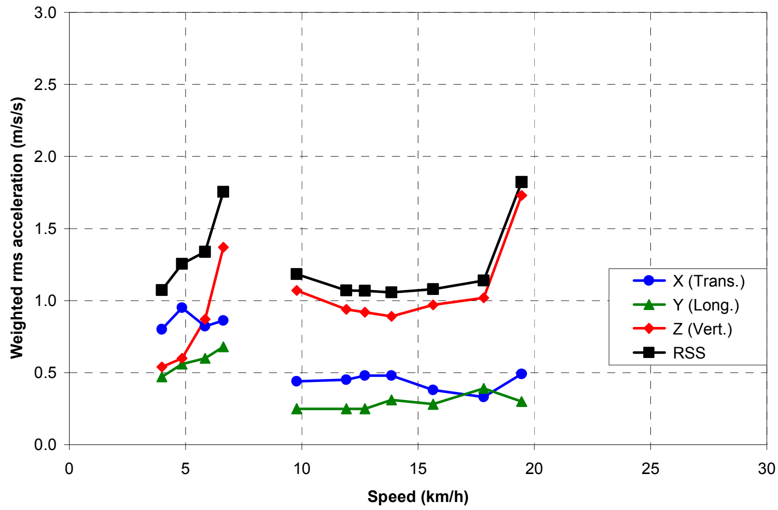

Figure 8.1: New Holland TS115 floor acceleration

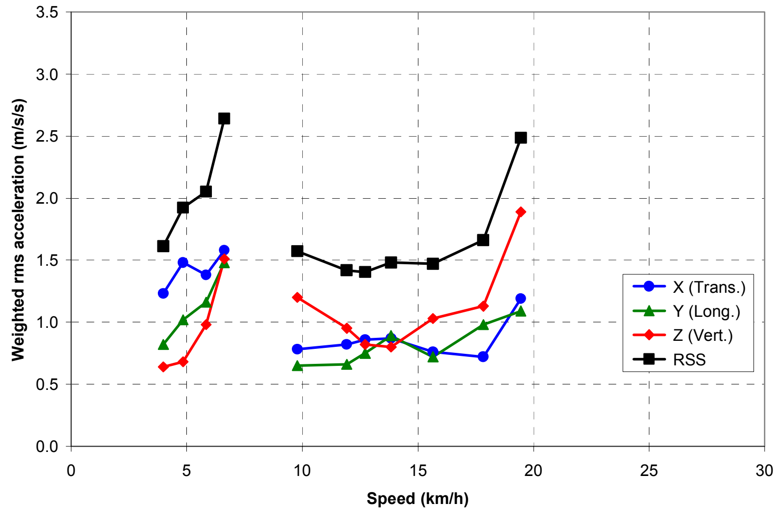

Figure 8.2: New Holland TS115 seat acceleration

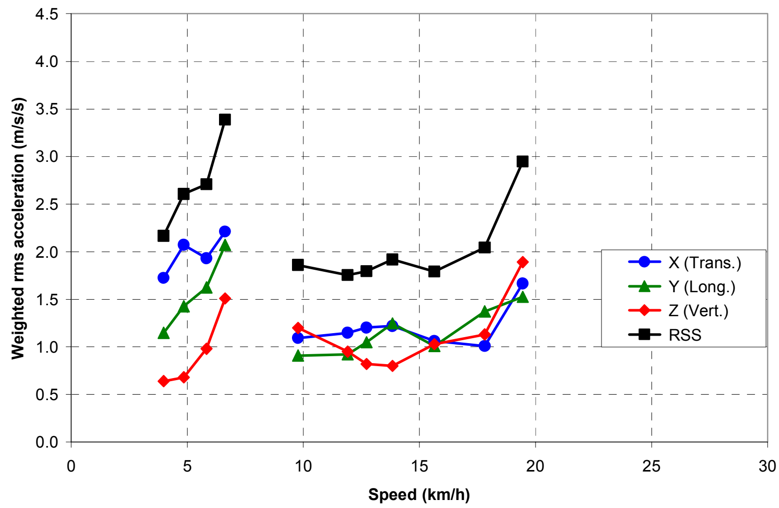

Figure 8.3: New Holland TS115 seat acceleration (*1.4 multiplier*)

Figure 9
New Holland TS115 tractor

Figure 10
Renault Ares 620 RZ tractor

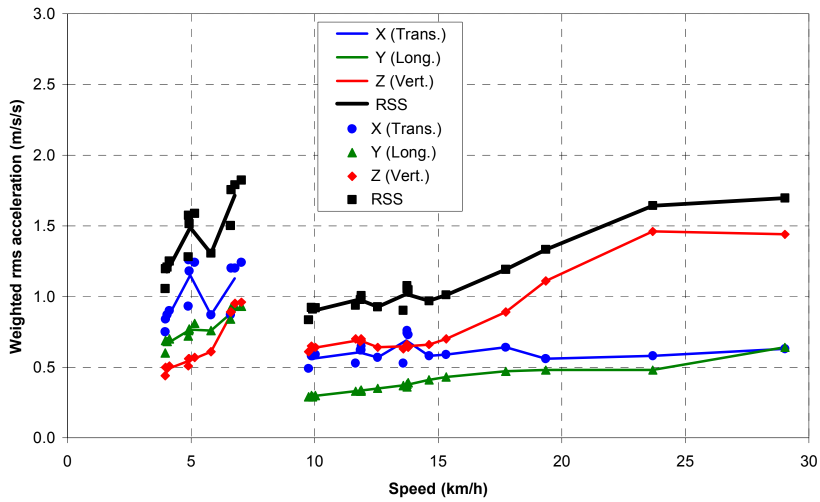

Figure 11.1: Renault Ares 620 RZ floor acceleration

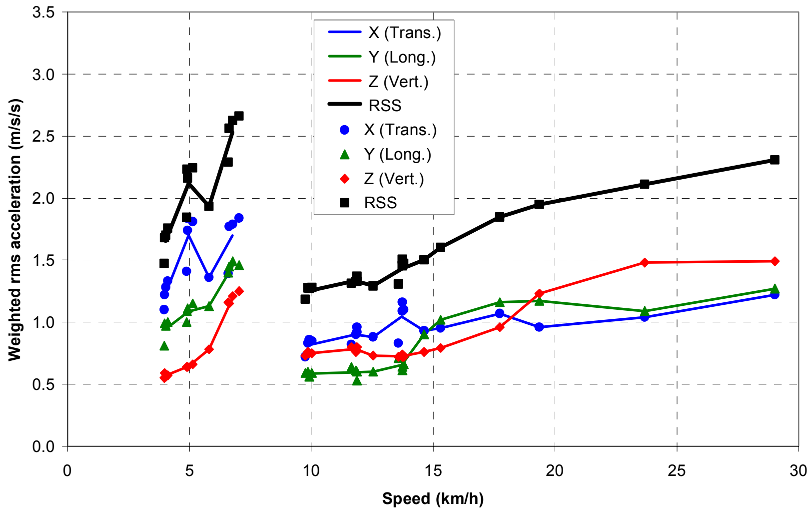

Figure 11.2: Renault Ares 620 RZ seat acceleration

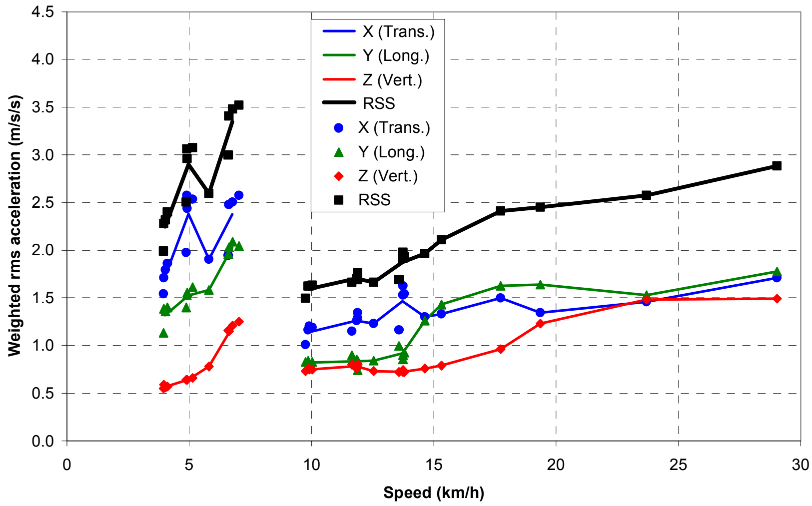

Figure 11.3: Renault Ares 620 RZ seat acceleration (*1.4 multiplier*)

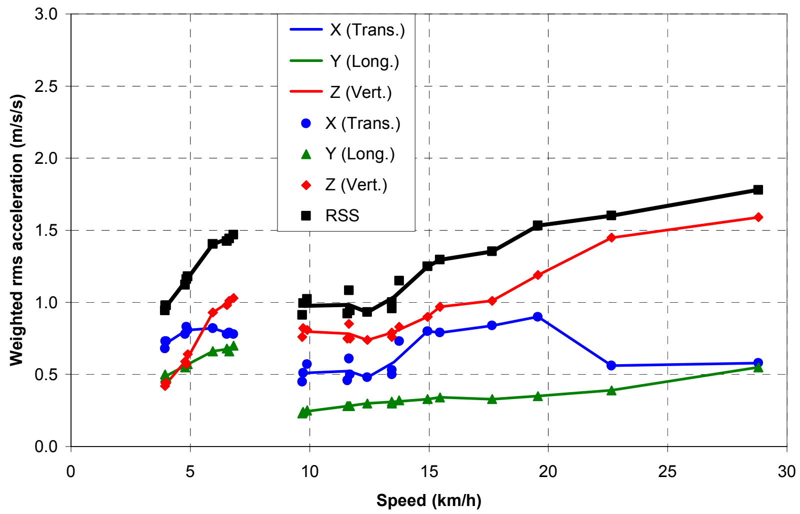

Figure 12.1: New Holland TM165 floor acceleration

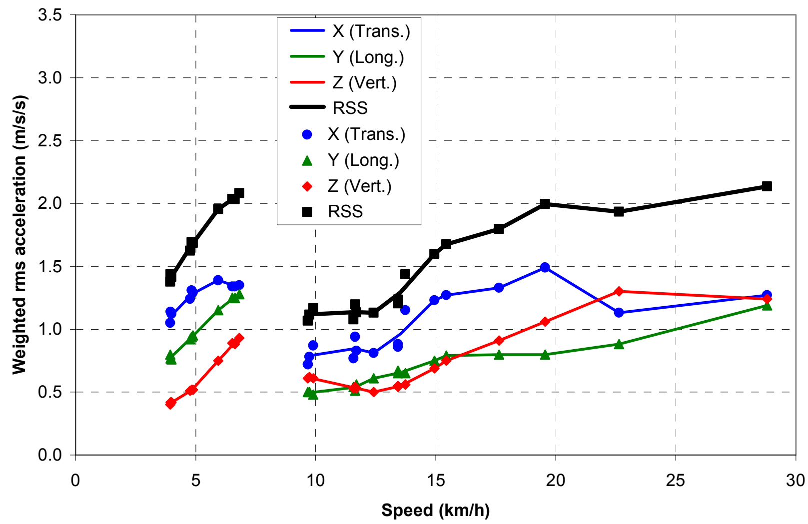

Figure 12.2: New Holland TM165 seat acceleration

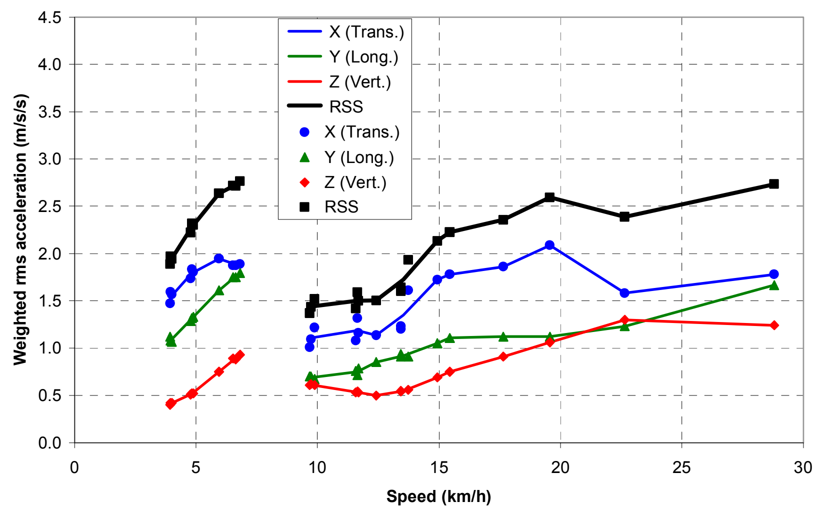

Figure 12.3: New Holland TM165 seat acceleration (*1.4 multiplier*)

Figure 13
New Holland TM165 tractor

5. DISCUSSION

5.1 GENERAL COMMENTS

As explained in Section 4, three sets of acceleration measurements are presented graphically for each tractor tested (with the exception of the MF 4255), one set originating from the floor-mounted accelerometers, the remaining two from those accelerometers mounted upon the seat cushion (see Figures 5, 6, 8, 11 & 12). These graphs depict frequency weighted rms acceleration levels recorded at the cab floor and the driver's seat, plotted against vehicle forward speed, during travel across both the ISO 35 m and ISO 100 m test tracks. Two sets of seat acceleration graphs are shown per tractor, the first in each case being the frequency weighted rms values "as measured"; the secod having been derived by applying a factor of 1.4 ("1.4 multiplier") to both horizontal (x & y axis) seat acceleration components. The latter data processing technique is required for vibration emission declaration (e.g. as specified in the draft revision of ISO 5008[5]). However, the acceptance of this "correction" is not universal, so the direct, unmodified "as measured" values are included for information. In general terms, the measured vibration magnitudes encountered in this instance were affected by:-

a) the nature of the surface over which the tractor was driven;
b) its forward speed;
c) aspects of the tractor design and configuration which affect its dynamic response.

The latter include vehicle mass (both overall and distribution between axles), ballast, tyre sizes (and corresponding inflation pressures), and the presence any suspension features e.g. axles and/or cab. The seat acceleration levels are also affected by the characteristics of the seat suspension system.

ISO 5008[5] attempts to reduce the number of test variables present in any given instance, by requesting removal of vehicle ballast (thereby tending to worst case conditions), and by specifying tyre pressures as the arithmetic mean of the ranges recommended by the vehicle manufacturer. However, in this particular investigation, the recommended tyre pressures for the axle / tyre loadings encountered in the unballasted condition, were generally at the bottom of the recommended tyre inflation pressure range (see Section 3.2), but this was at least consistent between the tractors. Some further consistency was provided by testing only 4WD tractors, and by using the same driver for all tests. Otherwise, it was an aim of this investigation to indicate likely variations resulting from different vehicle design features.

5.2 TEST SURFACES

The test surfaces used for the investigation are those specified in ISO 5008[5]: the ISO 35 m (rough) and ISO 100 m (smooth) artificial test tracks. As the vehicle travel speed ranges for each track do not overlap, measured vibration magnitudes from both test tracks are plotted against vehicle forward speed upon the same graph, thereby aiding comparison. The slower, rougher ISO 35 m track (which represents a ploughed field traversed at an angle to the furrows) provides more severe transverse and longitudinal acceleration inputs than the smoother track. The smoother ISO 100 m track (which represents an unmetalled farm roadway), provides an acceleration input which, at the cab floor, is dominated by the vertical component. This is generally reduced by the vehicle seat suspension, so that the horizontal components become important; increasingly so when the 1.4 multiplication factor is applied. In order to avoid any effect of the different seats fitted to the test tractors, the following comments (Sections 5.3 and 5.4) refer to characteristics that are demonstrated by the cab floor vibration results.

5.3 VEHICLE SPEED

The effect of vehicle travel speed upon results from the rougher (ISO 35 m) track is generally as would be expected, with vibration magnitudes increasing with speed rather more than in direct proportion. An exception is the John Deere 5300, whose transverse vibration reduces above a peak at 5 km/h. The effect of speed upon vibration magnitudes resulting from the smoother (ISO 100 m) track generally indicates a dip around 12 km/h, before an increase that appears to depend on the tractor model. For the smaller unsuspended tractors, the increase in vibration magnitude with speed is more marked than for the heavier, semi-suspended machines. The example of the New Holland TS115 typifies results that have been found with some other tractors, in that the increase with speed becomes rapidly more marked as travel speed exceeds 17 or 18 km/h. As mentioned above, these trends are caused by changes in the magnitude of the vertical component of vibration, as the horizontal components change much more gradually with increasing travel speed on the smoother track (ISO 100 m).

5.4 TRACTOR DESIGN FEATURES

The two lightest tractors, namely the John Deere 5300 and MF 4255, exhibited the highest vibration magnitudes on both test tracks. In this instance it is difficult to distinguish the ride vibration-reducing effects of vehicle (cab and front axle) suspensions from those of tractor mass, as the tractors with suspension were also the heaviest tested (Renault Ares 620 RZ & New Holland TM165). However, it is likely that the suspension systems are responsible for the leveling off in the increases in ride vibration magnitudes at higher travel speeds on the smoother (ISO 100 m) track, to the extent that it was possible to extend the track travel speed range up to 30 km/h for these vehicles. Had these tractors not been fitted with suspensions, it is likely (but not proven at this point) that an effect similar to that found for the New Holland TS115 (and other unsuspended tractors) may have been encountered, in which increasing travel speed is restricted by operator discomfort. It is also worthy of mention that the Renault may show to a slight disadvantage as the front tyre pressures could not be set lower than 0.95 bar, due to limited tyre size, whereas the front tyres of all the other tractors tested were able to accommodate their imposed loads at 0.6 bar inflation pressure.

5.5 OPERATOR SEATS

The acceleration measurements made upon the seats generally show some reduction in the vertical component, but some increases in the transverse and longitudinal components, compared with measurements made at the seat base (floor). The vertical component reduction is the result of the seat suspension system, whereas the increases in the horizontal acceleration components probably reflect the greater distance between the seat surface and the centres of rotation of the tractor chassis in pitch and roll, when compared with the distance between the seat mounting and these points. The horizontal components were possibly also exacerbated by some horizontal flexibility in the seat suspension mechanism and the seat cushion.

5.6 ISO 5008 REVISION

As a result of this study, its is appropriate to make some comments regarding the track travel speeds specified in the revision of ISO 5008[5].

First, for the rougher (ISO 35 m) track, a travel speed of 7 km/h gives magnitudes of vibration on lighter tractors which are too severe for test personnel to be exposed voluntarily, and clearly do not reflect realistic practical field use. The speed of 7 km/h is also associated with the largest measurement variation. A maximum speed of 6 km/h would be more appropriate.

Secondly, for the smoother (ISO 100 m) track, a travel speed of 10km/h is slower than realistic use ***on that type of surface***. It would be more realistic, and reduce testing time slightly, if speeds of 12, 14 and 16 km/h were used instead of 10, 12 and 14 km/h.

5.7 PHYSICAL AGENTS (VIBRATION) DIRECTIVE

The EU Physical Agents (Vibration) Directive (PA(V)D) originally proposed a whole-body vibration daily exposure limit value (ELV), standardised to an 8-hour reference period, of 1.15 ms^{-2} equivalent rms acceleration. However, amendments currently under discussion in Brussels are proposing this exposure limit value be reduced to 0.7 ms^{-2} rms The original ELV is exceeded by even the heaviest and best suspended tractor in these vibration emission tests.

However, it is necessary to stress that the values resulting from this investigation are for vibration ***emission***, and not for vibration ***exposure***. Their first use should be to compare different models / designs of tractor. The test conditions are consistent with the spirit of EN 1032, in that they represent relatively severe working conditions, although they cannot be claimed to be precisely at the 75th percentile of the range of common working exposures. For this reason, it is likely that they are higher than the average vibration levels likely to be encountered during any period of normal work, except for quite short-duration periods occurring intermittently during a working day. They should therefore ***not*** be taken as direct indications of the 8-hour equivalent rms vibration average levels defined in the draft PA(V)D.

Any relationship between these *emission* values and the 8-hour daily *exposure* values likely to be encountered with modern agricultural vehicles in typical operating conditions has yet to be proven. In particular some investigation is needed to determine whether the ride vibration-limiting effects of parameters such as tractor mass and/or suspension configuration, and their subsequent influence upon a vehicle operator's daily vibration exposure, can be determined from the performance of a given vehicle during standardised whole-body (ride) vibration emission tests. Only then will it be possible to decide whether the proposed limits are such that either they do or do not present the agricultural industry with a problem, or that the proposed limits can be met using best practice in agricultural vehicle design.

6. CONCLUSIONS

The objective of this work was to undertake a Pilot research study to quantify Whole-Body Vibration (WBV) emissions levels upon a limited range of modern agricultural tractors, operating in controlled conditions. With this in mind, the following conclusions may be drawn:-

- Vibration magnitudes experienced by the operator increased with travel speed over both test surfaces used;
- Whole-Body Vibration emission values for agricultural tractors are higher for lighter machines, compared with heavier models, and are reduced by the presence of cab and/or axle suspension systems;
- Heavier tractors, and those incorporating suspension systems, demonstrate smaller increases in ride vibration with increasing travel speed, compared with the lighter, unsuspended tractors tested;
- Under standard test conditions, the highest single-axis vibration *emission* magnitude (for all the tractors tested) was within the range 0.8 - 1.5 m/s^2. However, when the 1.4 multiplication factor is applied to the horizontal components (as required by ISO 2631:1997[15]), this range is increased to 1.2 - 2.0 m/s^2: this in considerably in excess of the WBV exposure limit value (ELV) proposed by the EU Physical Agents (Vibration) Directive (PA(V)D);
- On the rougher (ISO 35 m) test surface, within a travel speed range of 5 - 7 km/h, the most severe acceleration inputs occurred in the transverse axis (right angles to the direction of travel);
- On the smoother (ISO 100 m) test surface, within a travel speed range of 10 - 20 km/h, the most severe acceleration inputs occurred in the vertical axis: however this dominance switched to the longitudinal axis upon application of the (ISO 2631[15]) 1.4 multiplication factor;
- Vibration upon the vehicle seat is dominated by the horizontal components, because the seat suspension system reduces the severity of the vertical vibration component, and the greater height above the ground (compared with the cab floor / seat mounting) increases the effects of vehicle roll and pitch (the horizontal components);
- If the vibration *emission* values encountered in this study were to be endured by a tractor operator for 8 hours in a day, the ELV proposed by the PA(V)D would be exceeded. However, it is not known (at this stage) if tractors exhibiting these vibration *emission* values would necessarily expose their drivers to daily averaged vibration *exposure* levels that would exceed the PA(V)D limit (ELV);

- The revision of ISO 5008[5] should consider removal of the 7 km/h travel speed on the rougher (ISO 35 m) test surface, and replacement of the 10 km/h travel speed on the smoother (ISO 100 m) test surface by one of 16 km/h, to reflect developments in vehicle design.

7. RECOMMENDATIONS

In the light of the findings of this work, the following recommendations may be made:-

- Further investigation is required to establish linkage between the test track WBV emissions characteristics of a given vehicle, and subsequent WBV emissions and operator daily WBV exposures encountered during typical agricultural operations;
- It would be desirable to attempt short-term delay of the proposed EU PA(V)D until the findings of such an investigation (which is currently underway) become available.

8. ACKNOWLEDGEMENTS

Silsoe Research Institute and the RMS Vibration Test Laboratory gratefully acknowledge the assistance of the Agricultural Engineers Association, AGCO Ltd, cnh Global N.V., John Deere UK Ltd, and Renault Agriculture Ltd regarding loan of suitable vehicles for the purposes of the investigation.

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APPENDICES

APPENDIX 1 TEST VEHICLE SPECIFICATIONS

A1.1 John Deere 5300 Tractor

Make:-	John Deere
Model:-	5300
Engine power:-	40 kW (55 hp)
Vehicle mass:-	2692 kg (as tested)
Wheelbase:-	2.114 m
Track setting	1.4 m

Suspension features (in addition to operator's seat):- None

Ground drive system:- Unequal wheel four wheel drive
Goodyear Super Traction Radial tyres

	Front	Rear
Axle loadings:-	1105 kg	1587 kg
Tyre sizes:-	9.5 R 24	14.9 R 30
Tyre pressures:-	0.6 bar (8.7 lb/in^2)	0.6 bar (8.7 lb/in^2)

Operator's seat:- Grammer DS85H/3A - vertical axis mechanical spring & damper, scissor-type suspension. (e1 - I & II).
Operator's mass:- 77.5 kg

A1.2 Massey Ferguson 4255 Tractor

Make:-	Massey Ferguson
Model:-	4255
Engine power:-	71 kW (95 hp)
Vehicle mass:-	3778 kg (as tested)
Wheelbase:-	2.35 m
Track setting	1.626 m

Suspension features (in addition to operator's seat):- None

Ground drive system:- Unequal wheel four wheel drive
Goodyear Super Traction Radial tyres

	Front	Rear
Axle loadings:-	1508 kg	2270 kg
Tyre sizes:-	13.6 R 28	16.9 R 38
Tyre pressures:-	0.6 bar (8.7 lb/in^2)	0.6 bar (8.7 lb/in^2)

Operator's seat:- Grammer MSG85/731 - vertical axis mechanical spring & damper, scissor-type suspension. (e1 - II & III).
Operator's mass:- 77.5 kg

A1.3 New Holland TS115 Tractor

Make:-	New Holland
Model:-	TS 115
Engine power:-	75 kW (100 hp)
Vehicle mass:-	4616 kg (as tested)
Wheelbase:-	2.623 m
Track setting	1.626 m

Suspension features (in addition to operator's seat):- None

Ground drive system:- Unequal wheel four wheel drive
Goodyear Super Traction Radial tyres

	Front	Rear
Axle loadings:-	1749 kg	2867 kg
Tyre sizes:-	14.9 R 28	18.4 R 38
Tyre pressures:-	0.6 bar (8.7 lb/in^2)	0.6 bar (8.7 lb/in^2)

Operator's seat:-	Grammer MSG95/31 12V. (e1 - II & III).
Suspension type:-	Vertical axis:- air spring & damper, scissor-type Longitudinal axis:- mechanical spring & adjustable damper
Operator's mass:-	77.5 kg

A1.4 Renault Ares 620 RZ Tractor

Make:-	Renault
Model:-	Ares 620 RZ
Engine power:-	81 kW (109 hp)
Vehicle mass:-	4988 kg (as tested)
Wheelbase:-	2.750 m
Track setting	1.83 m

Suspension features
(in addition to operator's seat):- Fully-suspended *'Hydrostable'* cab, incorporating four vertical coil spring / damper units, Panhard rods & anti-roll bar.

Ground drive system:- Unequal wheel four wheel drive
Michelin XM25 radial tyres (front)
Continental Contract AC90 radial tyres (rear)

	Front	Rear
Axle loadings:-	2210 kg	2778 kg
Tyre sizes:-	13.6 R 28	16.9 R 38
Tyre pressures:-	0.95 bar (13.8 lb/in^2)	0.6 bar (8.7 lb/in^2)

Operator's seat:-	Isringhausen 6000/515. (e2 - I, II & III. 0.25).
Suspension type:-	Vertical axis:- mechanical spring & damper, scissor-type Longitudinal axis:- mechanical spring & damper
Operator's mass:-	77.5 kg

A1.5 New Holland TM165 Tractor

Make:-	New Holland
Model:-	TM165
Engine power:-	120 kW (160 hp)
Vehicle mass:-	6518 kg (as tested)
Wheelbase:-	2.787 m
Track setting	1.715 m

Suspension features (in addition to operator's seat):-	*'Terraglide'* self-levelling, gas-over-oil, front axle suspension system *'Comfort Ride'* cab suspension system; Coil springs, dampers & Panhard rods *(Cab rear)* Profiled rubber bushes *(Cab front)*
Ground drive system:-	Unequal wheel four wheel drive Goodyear DT820 radial tyres

	Front	Rear
Axle loadings:-	2619 kg	3899 kg
Tyre sizes:-	540/65 R 30	650/65 R 30
Tyre pressures:-	0.6 bar (8.7 lb/in^2))	0.6 bar (8.7 lb/in^2)

Operator's seat:-	Sears deluxe air suspension seat	
	Suspension unit:-	SA15748 (e11 - I, II & III. 1294)
	Seat unit:-	SA15803
Suspension type:-	Vertical axis:-	air spring & adjustable damper, scissor-type
	Longitudinal axis:-	mechanical spring & adjustable damper
Operator's mass:-	77.5 kg	

APPENDIX 2 WHOLE-BODY VIBRATION TEST DATA

A2.1 John Deere 5300

Actual	Floor acceleration (m/s/s)							
Speed(km/h)	X (Trans.)		Y (Long.)		Z (Vert.)		RSS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
3.9	1.32	0.038	0.86	0.021	0.67	0.015	1.71	0.034
5.2	1.65	0.075	0.98	0.021	0.93	0.010	2.13	0.049
6.3	1.61		1.18		1.16		2.31	
6.9	1.44	0.051	1.21	0.025	1.30	0.025	2.29	0.059
9.8	0.72	0.006	0.33	0.010	1.02	0.031	1.30	0.025
11.8	0.78	0.025	0.36	0.006	0.93	0.031	1.27	0.036
13.5	0.80		0.40		1.17		1.47	
14.3	0.83	0.026	0.41	0.000	1.38	0.021	1.66	0.010
14.2	0.86		0.40		1.35		1.65	
16.4	0.87		0.38		1.92		2.14	
17.6	1.00		0.40		2.22		2.47	
19.8	0.93		0.40		2.48		2.68	

Actual	Seat acceleration, direct (m/s/s)							
Speed(km/h)	X (Trans.)		Y (Long.)		Z (Vert.)		RSS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
3.9	1.60	0.040	1.12	0.036	0.67	0.012	2.07	0.025
5.2	2.03	0.055	1.33	0.012	0.89	0.021	2.59	0.033
6.3	2.03		1.64		1.20		2.87	
6.9	1.87	0.075	1.64	0.021	1.63	0.246	2.98	0.193
9.8	0.97	0.006	0.48	0.010	0.88	0.010	1.39	0.008
11.8	1.03	0.025	0.56	0.020	0.76	0.036	1.39	0.043
13.5	1.08		0.72		1.07		1.68	
14.3	1.08	0.020	0.76	0.012	1.25	0.020	1.82	0.013
14.2	1.14		0.74		1.23		1.83	
16.4	1.16		0.77		1.71		2.21	
17.6	1.29		0.81		2.03		2.54	
19.8	1.25		0.77		2.15		2.60	

Actual	Seat acceleration, 1.4 multiplier (m/s/s)							
Speed(km/h)	X (Trans.)		Y (Long.)		Z (Vert.)		RSS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
3.9	2.24	0.057	1.57	0.050	0.67	0.012	2.82	0.034
5.2	2.85	0.077	1.86	0.016	0.89	0.021	3.51	0.051
6.3	2.84		2.30		1.20		3.85	
6.9	2.62	0.106	2.30	0.029	1.63	0.246	3.85	0.192
9.8	1.35	0.008	0.67	0.014	0.88	0.010	1.75	0.011
11.8	1.44	0.035	0.78	0.028	0.76	0.036	1.81	0.051
13.5	1.51		1.01		1.07		2.11	
14.3	1.51	0.028	1.07	0.016	1.25	0.020	2.23	0.021
14.2	1.60		1.04		1.23		2.27	
16.4	1.62		1.08		1.71		2.59	
17.6	1.81		1.13		2.03		2.94	
19.8	1.75		1.08		2.15		2.97	

A2.2 Massey Ferguson 4255

Actual	*Floor acceleration (m/s/s)*							
Speed(km/h)	*X (Trans.)*		*Y (Long.)*		*Z (Vert.)*		*RSS*	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
4.0	1.16	0.015	0.78	0.010	0.52	0.017	1.49	0.014
4.7	1.45	0.015	0.83	0.025	0.70	0.017	1.81	0.026
5.8	1.44		0.86		0.85		1.88	
6.5	1.46	0.049	0.89	0.042	1.10	0.026	2.03	0.061
9.8	0.63	0.015	0.28	0.006	1.06	0.021	1.26	0.025
12.1	0.67	0.025	0.30	0.007	0.92	0.015	1.18	0.028
12.9	0.70		0.31		0.86		1.15	
13.8	0.73	0.012	0.33	0.000	0.97	0.025	1.26	0.014
14.8	0.79		0.37		1.12		1.42	
16.0	0.82		0.36		1.34		1.61	
17.8	0.93		0.38		1.78		2.04	
20.3	0.81		0.33		1.80		2.00	

Actual	*Seat acceleration, direct (m/s/s)*							
Speed(km/h)	*X (Trans.)*		*Y (Long.)*		*Z (Vert.)*		*RSS*	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
4.0	1.32	0.060	1.10	0.125	0.80	0.023	1.89	0.106
4.7	1.38	0.140	1.18	0.040	1.31	0.068	2.24	0.085
5.8	1.41		1.35		1.86		2.70	
6.5	1.59	0.401	2.10	0.239	2.66	0.210	3.75	0.415
9.8	1.07	0.161	0.82	0.055	1.80	0.140	2.25	0.204
12.1	0.95	0.057	0.88	0.309	1.34	0.272	1.87	0.358
12.9	1.00		1.10		1.51		2.12	
13.8	1.24	0.131	1.23	0.224	1.74	0.098	2.48	0.093
14.8	1.28		1.54		2.21		2.98	
16.0	1.16		1.24		1.88		2.53	
17.8	1.31		1.49		2.79		3.42	
20.3	1.60		1.39		2.95		3.63	

Actual	*Seat acceleration, 1.4 multiplier (m/s/s)*							
Speed(km/h)	*X (Trans.)*		*Y (Long.)*		*Z (Vert.)*		*RSS*	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
4.0	1.84	0.084	1.54	0.175	0.80	0.023	2.53	0.161
4.7	1.94	0.196	1.66	0.057	1.31	0.068	2.86	0.146
5.8	1.97		1.89		1.86		3.31	
6.5	2.22	0.561	2.94	0.335	2.66	0.210	4.54	0.572
9.8	1.50	0.225	1.14	0.077	1.80	0.140	2.61	0.254
12.1	1.33	0.080	1.24	0.433	1.34	0.272	2.26	0.430
12.9	1.40		1.54		1.51		2.57	
13.8	1.74	0.184	1.73	0.313	1.74	0.098	3.01	0.119
14.8	1.79		2.16		2.21		3.57	
16.0	1.62		1.74		1.88		3.03	
17.8	1.83		2.09		2.79		3.94	
20.3	2.24		1.95		2.95		4.18	

A2.3 New Holland TS115

Actual	Floor acceleration (m/s/s)							
Speed(km/h)	X (Trans.)		Y (Long.)		Z (Vert.)		RSS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
4.0	0.80		0.47		0.54		1.07	
4.8	0.95		0.56		0.60		1.26	
5.8	0.82		0.60		0.87		1.34	
6.6	0.86		0.68		1.37		1.75	
9.8	0.44		0.25		1.07		1.18	
11.9	0.45		0.25		0.94		1.07	
12.7	0.48		0.25		0.92		1.07	
13.8	0.48		0.31		0.89		1.06	
15.7	0.38		0.28		0.97		1.08	
17.8	0.33		0.39		1.02		1.14	
19.5	0.49		0.30		1.73		1.82	

Actual	Seat acceleration, direct (m/s/s)							
Speed(km/h)	X (Trans.)		Y (Long.)		Z (Vert.)		RSS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
4.0	1.23		0.82		0.64		1.61	
4.8	1.48		1.02		0.68		1.92	
5.8	1.38		1.16		0.98		2.05	
6.6	1.58		1.48		1.51		2.64	
9.8	0.78		0.65		1.20		1.57	
11.9	0.82		0.66		0.95		1.42	
12.7	0.86		0.75		0.82		1.41	
13.8	0.87		0.89		0.80		1.48	
15.7	0.76		0.72		1.03		1.47	
17.8	0.72		0.98		1.13		1.66	
19.5	1.19		1.09		1.89		2.49	

Actual	Seat acceleration, 1.4 multiplier (m/s/s)							
Speed(km/h)	X (Trans.)		Y (Long.)		Z (Vert.)		RSS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
4.0	1.72		1.15		0.64		2.17	
4.8	2.07		1.43		0.68		2.61	
5.8	1.93		1.62		0.98		2.71	
6.6	2.21		2.07		1.51		3.39	
9.8	1.09		0.91		1.20		1.86	
11.9	1.15		0.92		0.95		1.75	
12.7	1.20		1.05		0.82		1.80	
13.8	1.22		1.25		0.80		1.92	
15.7	1.06		1.01		1.03		1.79	
17.8	1.01		1.37		1.13		2.04	
19.5	1.67		1.53		1.89		2.95	

Note: First tractor tested, no replicates, therefore no standard deviation values

A2.4 Renault Ares 620 RZ

Actual Speed(km/h)	Floor acceleration (m/s/s)							
	X (Trans.)		Y (Long.)		Z (Vert.)		RSS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
4.0	0.84	0.065	0.67	0.046	0.49	0.031	1.18	0.084
5.0	1.15	0.152	0.77	0.037	0.55	0.027	1.49	0.142
5.8	0.87		0.76		0.61		1.31	
6.8	1.13	0.173	0.91	0.044	0.92	0.038	1.72	0.147
9.9	0.56	0.047	0.30	0.006	0.64	0.017	0.90	0.042
11.8	0.61	0.052	0.33	0.005	0.69	0.010	0.98	0.030
12.5	0.57		0.35		0.64		0.93	
13.7	0.69	0.107	0.38	0.013	0.65	0.015	1.02	0.079
14.6	0.58		0.41		0.66		0.97	
15.3	0.59		0.43		0.70		1.01	
17.7	0.64		0.47		0.89		1.19	
19.4	0.56		0.48		1.11		1.33	
23.7	0.58		0.48		1.46		1.64	
29.0	0.63		0.64		1.44		1.70	

Actual Speed(km/h)	Seat acceleration, direct (m/s/s)							
	X (Trans.)		Y (Long.)		Z (Vert.)		RSS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
4.0	1.23	0.099	0.94	0.089	0.57	0.017	1.65	0.125
5.0	1.70	0.198	1.09	0.063	0.65	0.010	2.12	0.188
5.8	1.36		1.13		0.78		1.93	
6.8	1.70	0.207	1.45	0.037	1.19	0.046	2.53	0.169
9.9	0.82	0.065	0.59	0.017	0.75	0.013	1.25	0.046
11.8	0.90	0.059	0.60	0.047	0.78	0.021	1.33	0.024
12.5	0.88		0.60		0.73		1.29	
13.7	1.05	0.147	0.66	0.042	0.73	0.010	1.43	0.087
14.6	0.93		0.90		0.76		1.50	
15.3	0.95		1.02		0.79		1.60	
17.7	1.07		1.16		0.96		1.85	
19.4	0.96		1.17		1.23		1.95	
23.7	1.04		1.09		1.48		2.11	
29.0	1.22		1.27		1.49		2.31	

Actual Speed(km/h)	Seat acceleration, 1.4 multiplier (m/s/s)							
	X (Trans.)		Y (Long.)		Z (Vert.)		RSS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
4.0	1.73	0.139	1.32	0.125	0.57	0.017	2.25	0.178
5.0	2.38	0.277	1.52	0.089	0.65	0.010	2.90	0.269
5.8	1.90		1.58		0.78		2.60	
6.8	2.38	0.290	2.03	0.052	1.19	0.046	3.35	0.240
9.9	1.14	0.090	0.82	0.024	0.75	0.013	1.59	0.066
11.8	1.26	0.082	0.83	0.065	0.78	0.021	1.70	0.043
12.5	1.23		0.84		0.73		1.66	
13.7	1.46	0.205	0.92	0.059	0.73	0.010	1.87	0.129
14.6	1.30		1.26		0.76		1.96	
15.3	1.33		1.43		0.79		2.11	
17.7	1.50		1.62		0.96		2.41	
19.4	1.34		1.64		1.23		2.45	
23.7	1.46		1.53		1.48		2.58	
29.0	1.71		1.78		1.49		2.88	

Note: measurements from more than one day combined

A2.5 New Holland TM165

Actual	*Floor acceleration (m/s/s)*							
Speed(km/h)	*X (Trans.)*		*Y (Long.)*		*Z (Vert.)*		*RSS*	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
4.0	0.71	*0.029*	0.49	*0.012*	0.43	*0.012*	0.97	*0.020*
4.8	0.81	*0.025*	0.57	*0.015*	0.60	*0.036*	1.15	*0.029*
5.9	0.82		0.66		0.93		1.40	
6.7	0.78	*0.006*	0.68	*0.020*	1.01	*0.025*	1.45	*0.022*
9.8	0.51	*0.060*	0.24	*0.010*	0.80	*0.032*	0.98	*0.057*
11.6	0.52	*0.078*	0.28	*0.000*	0.78	*0.058*	0.98	*0.087*
12.4	0.48		0.30		0.74		0.93	
13.5	0.59	*0.125*	0.31	*0.010*	0.79	*0.035*	1.04	*0.101*
14.9	0.80		0.33		0.90		1.25	
15.5	0.79		0.34		0.97		1.30	
17.6	0.84		0.33		1.01		1.35	
19.6	0.90		0.35		1.19		1.53	
22.6	0.56		0.39		1.45		1.60	
28.8	0.58		0.55		1.59		1.78	

Actual	*Seat acceleration, direct (m/s/s)*							
Speed(km/h)	*X (Trans.)*		*Y (Long.)*		*Z (Vert.)*		*RSS*	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
4.0	1.10	*0.047*	0.78	*0.021*	0.41	*0.012*	1.41	*0.030*
4.8	1.28	*0.036*	0.94	*0.015*	0.52	*0.006*	1.67	*0.037*
5.9	1.39		1.15		0.75		1.95	
6.7	1.34	*0.006*	1.26	*0.017*	0.90	*0.026*	2.05	*0.026*
9.8	0.79	*0.075*	0.49	*0.012*	0.61	*0.006*	1.12	*0.049*
11.6	0.85	*0.086*	0.54	*0.025*	0.53	*0.006*	1.14	*0.059*
12.4	0.81		0.61		0.50		1.13	
13.5	0.96	*0.162*	0.66	*0.012*	0.55	*0.010*	1.29	*0.125*
14.9	1.23		0.75		0.69		1.60	
15.5	1.27		0.79		0.75		1.67	
17.6	1.33		0.80		0.91		1.80	
19.6	1.49		0.80		1.06		2.00	
22.6	1.13		0.88		1.30		1.93	
28.8	1.27		1.19		1.24		2.14	

Actual	*Seat acceleration, 1.4 multiplier (m/s/s)*							
Speed(km/h)	*X (Trans.)*		*Y (Long.)*		*Z (Vert.)*		*RSS*	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
4.0	1.54	*0.066*	1.09	*0.029*	0.41	*0.012*	1.93	*0.041*
4.8	1.79	*0.050*	1.31	*0.021*	0.52	*0.006*	2.28	*0.052*
5.9	1.95		1.61		0.75		2.63	
6.7	1.88	*0.008*	1.76	*0.024*	0.90	*0.026*	2.73	*0.030*
9.8	1.11	*0.106*	0.69	*0.016*	0.61	*0.006*	1.44	*0.074*
11.6	1.19	*0.121*	0.75	*0.035*	0.53	*0.006*	1.50	*0.086*
12.4	1.13		0.85		0.50		1.51	
13.5	1.35	*0.227*	0.92	*0.016*	0.55	*0.010*	1.72	*0.180*
14.9	1.72		1.05		0.69		2.13	
15.5	1.78		1.11		0.75		2.22	
17.6	1.86		1.12		0.91		2.36	
19.6	2.09		1.12		1.06		2.59	
22.6	1.58		1.23		1.30		2.39	
28.8	1.78		1.67		1.24		2.73	

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