Effect of Tyre Pressure and Wheel Loads on Whole-Body Vibration Characteristics of Tractors

Cutini M., Romano E., Bisaglia C.
Consiglio per la Ricerca in Agricoltura – Unità di Ricerca per l'Ingegneria Agraria; via Milano 43, 24047 Treviglio BG, Italy; E-mail: maurizio.cutini@entecra.it

Abstract
Agricultural vehicle operators are exposed to high levels of Whole Body Vibrations (WBV), which is related, above all, to surface irregularities and forward speed. European Parliament Directive 2002/44/EEC sets the minimum requirements for the protection of workers from risks to their health and safety due to exposure to mechanical vibrations.
Tractor tyres play a key role in damping vibrations, their response varies according to the mass and inflation pressure and they have to be taken into account at different forward speeds. This study was aimed at evaluating the impact of each parameter on driver comfort. Two tests were carried out using tractors with different tyres mounted. Forward speed was found to be the most significant factor in the determination of operator comfort, and comfort depreciated with increasing speed; on average, the comfort index passed from 0.6 m/s^2 at 6.7 m/s to 1.2 m/s^2 at 14.2 m/s. Lower inflation pressure offers better results in terms of comfort index (CI), yet it is more critical under resonance conditions. The addition of ballast moderates CI variations and diminishes the effect of speed, as well as the resonance peaks. A complete methodology was carried out and validated.

Keywords: operator comfort, safety, testing configuration

Introduction
The professional drivers are exposed at whole body vibrations (Okunribido, 2006) and, in particular, agricultural vehicle operators could be at risk of high levels of exposure (Scarlett et al., 2007).
The protection of workers from risks to their health and safety due to exposure to mechanical hand/arm vibrations and whole body vibration is reported in the European Parliament Directive 2002/44/EEC (EEC, 2002), that defines the minimum safety requirements. Moreover, in 2008, Italy adopted a specific national regulation on physical agents control (Decree no. 81/2008).
This project, focused on whole body vibration, aims to define the correct tractor settings in order to evaluate comfort values during transport. In fact, the tyres' damping effectiveness depends on factors such as wheels eccentricity, load, pressure (Sherwin et al., 2004), resonance frequency, and elasticity characteristics (Taylor et al., 2000).
A first methodological approach on the role of the tires on the operator comfort was been developed by the CRA-ING Laboratory of Treviglio (Cutini et al., 2007) and allowed to focus the main boundary conditions (step forward speed, pressure and mass configuration) to be used for further research steps (Cutini et al., 2008). The analysis derived from the obtained results allowed to introduce the statistic approach herewith presented.

Theoretical considerations
As agricultural tyres can be considered as a system of springs and dumper, it is necessary, during tests on comfort, to take into account the factors that could affect the elastic behavior of the tyres and to evaluate their influence on the results. These factors are: the tractor mass distribution (impact on the value of resonance frequency), the tyre pressure (impact on tyre

stiffness) and the forward speed (which characterizes the solicitation frequency input). In order to reduce the variables, a flat test track surface was selected so that the source of vibrations resulted from the combination of tyre eccentricity and forward speed, and the vehicles had no suspension devices (or blocked when possible), apart of those on the seat.
The ISO 2631:1997 testing standard was used for this study to assess vibration exposure. The total vibration value of the weighted root-mean-square (RMS) acceleration was determined from the vibration in the orthogonal coordinates, calculated as follows:

$$a_v = (k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2)^{1/2}$$

where k_i is a multiplying factor defined in the standard and a_{wi} is the weighted RMS acceleration. The filters for weighing the measured acceleration are defined in the standard and depend on the point of location and the solicitated axle. The Comfort Index (CI) is the overall total vibration value, determined from the root-sum-of-squares of the point vibration values.

Materials and methods

Tests were carried on a 400-meter, straight stretch of test track with an asphalt surface at the CRA-ING Laboratory in Treviglio, North Italy.
Considering the range of speeds that can affect comfort in when a tractor works on smooth surfaces (7-14 ms^{-1}) and with the aim of investigating the critical speed-related tractor settings for comfort, a first test (T1) was conducted to investigate the influence of pressure, mass distribution and speed. After analyzing the results, a second test (T2), focused on a more detailed investigation of the same parameters, was carried out. The two methodologies were:

- Test 1 (T1)
  - 3 pressure configurations (kPa): 160 (16); 200 (20); 240 (24);
  - 2 ballast configurations: ballasted (Z); non ballasted (N);
  - 1.39 ms-1 (5 kmh^{-1}) stepped forward speed from 6.94 to 13.9.
- Test (T2)
  - 2 pressure configurations (kPa): 120 (12); 160 (16);
  - 2 ballast configurations: ballasted (Z); non ballasted (N);
  - 0.83 ms-1 (3 kmh^{-1}) stepped forward speed from 6.67 to 14.17.

Different makes of tyres were used, and their specifications were

- Test 1 (Tires' code: T1A, T1B, T1C):
  - front: 600/70 R30;
  - rear: 710/70 R42.
- Test 2 (Tires' code: T2a; T2b; T2c; T2d):
  - front: 520/70 R38;
  - rear: 420/70 R28.

The solicitations at the three points of seat, back and X and Y rotational axes (pitch and roll) in both tests, and the solicitation at the feet in T1, were taken into account.
Triaxial sensors were fitted onto the seat, at the back of the operator and onto the cabin floor, near the foot under the pedal brake. A monoaxial accelerometer measured the vertical acceleration at the front of the cab, and the second monoaxial accelerometer was placed on the right side of the cab, in order to obtain, in combination with the vertical channel of the triaxial accelerometer at the back, the driver's pitch and roll respectively.
A randomized complete block design (RCBD) was adopted. Each block was represented by the make of each tyre. CRAN's R statistical programme (Comprehensive R Archive Network) from WU (Wien-Umgebung), Austria, was used for the data analysis. The plots used for each

treatment consisted of 400 m of tarmac surface. The independent variables were: the make of the tyre, the tractor speed, the mass distribution on the tractor and the tyre inflation pressure.
Data processing was carried out on the results from the vectors (X, Y and Z) of the seat, the back and the rotation components.

Results

In T1 the CI value varied from 0.4-0.8 ms^{-2} at 6.9 ms^{-1} and 0.6 and 1.2 ms^{-2}.at 13.9 ms^{-1} The CI value increased with speed, but in a non-linear fashion (Fig. 1). Some speeds are critical for the resonance of the front and/or rear tyres.

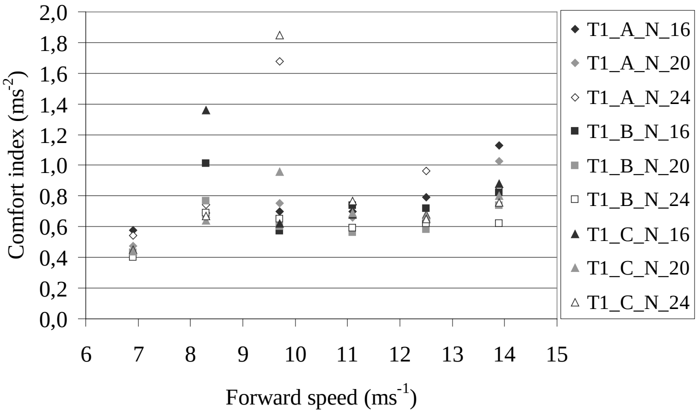

Figure 1. CI values obtained in T1 with: different tyre marks (A, B, C); the tractor without ballast (N); the pressure of the tyres at 160 kPa (16), 200 kPa (20) and 240 kPa (24).

In fact, the value changed from 0.6 ms^{-2} up to 1.8 ms^{-2} at the same forward speed. No difference was observed between the ballasted and non ballasted setting values but, in resonance conditions, the non ballasted setting was less comfortable, with values ranging from 0.9 ms^{-2} to 1.4 ms^{-2}. The same considerations can be made concerning pressure: no appreciable differences were observed for the CI value, apart from resonance conditions, where the same condition changed the CI value from 0.6 ms^{-2}, at 160 kPa, to 1.7 ms^{-2} at 240 kPa. The highest discomfort values, 1.7 - 1.8 ms^{-2}, were obtained at 240 kPa but were limited to critical speeds.

Test2

The results obtained with T1 indicated that it was necessary to carry out a more detailed investigation of the critical speeds. The step was changed to 0.83 ms^{-1}, and the analyzed pressures were also changed. Two configurations were considered: a nominal one (160 kPa) and one at a lower pressure (120 kPa). The results confirm that a 0.83 ms^{-1} step was necessary for the importance of the front tires resonance.
The CI values (Fig. 2) in this test showed very limited differences, from 0.5 to 0.8 ms^{-2}, at low speeds, 6.7 and 7.5 ms^{-1}. This fact indicates that the starting speed of interest in the test is 8.3 ms^{-1}.
In terms of inflation pressure, T2 test gave more significant results.

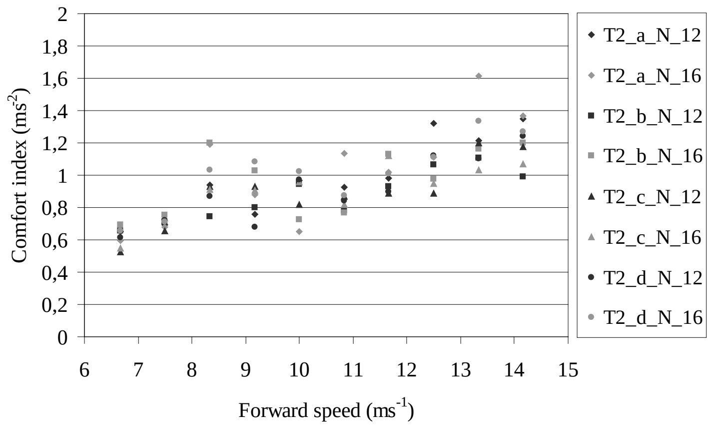

Figure 2. CI values obtained in T2 with: different tyre marks (a, b, c, d); the tractor without ballast (N); the pressure of the tyres at 120 kPa (12) and 160 kPa (16).

An higher inflation pressure value, generally gave a slightly higher CI value but, more importantly, the effect of switching resonance frequency, and consequently of the relevant speed. The effect of increasing speed and resonance peaks diminishes when the tractor is ballasted, and this leads to a levelling of the CI values.

Discussion

The maximum value for all the data on a single solicitation axis was 1.54 ms^{-2}, a value that was recorded under low pressure and no ballast conditions by vector X of the back component of CI; the minimum value was 0.01, which was recorded under low pressure and ballasted conditions by vector Y of the seat component of CI. Statistical analysis (tab. 1 and tab. 2) showed significance for forward speed, in particular in T2, and inflation pressure both on CI, both on its components (seat and back). The rotation component was not influenced from pressure. The impact of mass resulted significance in analysis on seat. Statistical significance for tyre make variable was find only on seat in T1.

Table 1. Comparison between T1 and T2

Variable	CI T1	CI T2	SEAT T1	SEAT T2	BACK T1	BACK T2	ROT T1	ROT T2	CI T1+T2
MK	.		**						
SP		***	*	***	.	***		***	***
MS			**	***	.				
PR		***		**		***			**
MK x SP									
MK x MS									
SP x MS	**	*	***	**	**	*			**
MK x PR									
SP x PR	.		**	.	.				.
MS x PR									
MK x SP x MS									
MK x SP x PR						.			
MK x MS x PR						.			
SP x MS x PR		**	.	*		**		.	*

MK=make; SP=speed; MS=mass; PR=pressure
Signif. Codes: "***"=0.001; "**"=0.01; "*"=0.05; "."=0.1; " ">1

Table 2. Analysis on the CI components

	SEAT				BACK				ROTATION		
Variable	TOT	X	Y	Z	TOT	X	Y	Z	TOT	X	Y
MK							**				.
SP	***	***	***	***	***	***	***	***	***	***	***
MS	***	***	***				***	***			
PR	**			***	***	***	*				
MK x SP											
MK x MS		*	*								
SP x MS	**	*		***	*	.	.	*			***
MK x PR											
SP x PR	.			*				*			*
MS x PR											
MK x SP x MS											
MK x SP x PR		**			.	**					
MK x MS x PR		*			.						
SP x MS x PR	*	**		*	**	**			.		

MK=make; SP=speed; MS=mass; PR=pressure
Signif. Codes: "***"=0.001; "**"=0.01; "*"=0.05; "."=0.1; " ">1

Analysis on seat showed an impact of mass on X and Y vectors and of pressure on Z component.
The developed methodology for the testing procedure involves:

- A starting speed of 8.3 ms^{-1};
- A step forward speed of 0.83 ms^{-1};
- Two pressure configurations: P1≤120 MPa; P2≥160 MPa;
- Two ballast configurations: not ballasted, ballasted;
- Main sensors: triaxial accelerometers at the seat and back.

Conclusions

Operator comfort has been evaluated on two tractors during road transfer fitted with different tires. The CI (ISO 2631:1997) was evaluated taking into consideration different mass distributions, tyre inflation pressures and forward speeds. Forward speed resulted to be the most significant factor. A lower inflation pressure generally provides better results, in terms of comfort index, but it is more critical in resonance conditions. Ballasting balances the CI values and diminishes the effect of increased speed as well as the resonance peaks. The study has shown the enormous importance of adopting suitable tractor settings, above all by working on mass and tyre pressure at the desired forward speed, in order to obtain better results, in terms of operator comfort, for agricultural tractors.

Acknowledgements

The research was funded within the framework of the Italian Ministry of Agricultural and Forestry Policies project "Vibra.M.Ag." (Evaluation and control of the vibrations in mechanical agricultural systems with research methods based on a four-poster test rig).

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