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GROUND SOIL INPUT CHARACTERISTICS DETERMINING AGRICULTURAL TRACTORS DYNAMICS

M. Cutini, R. Deboli, A. Calvo, C. Preti, M. Brambilla, C. Bisaglia

The authors are Maurizio Cutini, Researcher, Massimo Brambilla, Researcher and Carlo Bisaglia, Senior researcher, Consiglio per la ricerca in agricoltura e l’analisi dell’economia agraria (CREA) – Unità di Ricerca per l’Ingegneria Agraria; Laboratorio di Treviglio (CREA-ING), Treviglio (BG), Italy; Roberto Deboli, Senior Researcher, and Christian Preti, Researcher, Italian National Research Council - Institute for Agricultural and Earthmoving Machines (IMAMOTER), Turin, Italy; Angela Calvo, Associated Professor, Dipartimento di Scienze Agrarie, Forestali e Alimentari (DISAFA) – University of Turin, Turin, Italy. Corresponding author: Maurizio Cutini, Consiglio per la ricerca in agricoltura e l’analisi dell’economia agraria (CREA)– Unità di Ricerca per l’Ingegneria Agraria; Laboratorio di Treviglio (CREA-ING), Via Milano 43, 24047 Treviglio (BG), Italy; phone: 039-0363-46303; e-mail: maurizio.cutini@crea.gov.it.

ABSTRACT.

Whole body vibrations are among the risk factors of professional diseases in agricultural operators: studying vibrations source dynamics is therefore fundamental to improve vehicle comfort and safety. This study analyses the forces acting under the tires of one tractor run in twenty nine different settings both on a standard “ISO 5008” test-track and three terrain surfaces. For each setting the accelerations acquired at tractor’s hubs were reproduced on a four poster test bench: for each surface the actuators’ vertical displacement reproducing the test track was obtained. Subsequently, the spectra of the twenty nine replicated ground inputs were analyzed. All of them showed a similar shape in terms of frequency pointing out that solicitations originating from different agricultural surfaces belonged to a specific range of frequencies. Because of this, a remarkable simplification and standardization in the analysis of tractors’ dynamics, comfort and materials resistance can be introduced.

Keywords.

Agricultural tires, Four poster test bench, Ground input, Safety, Soil profile

1 Introduction

Prolonged exposure to risk factors during work-related activities results in occupational diseases that represent an extremely important cost under human and socio-economic points of view (Litchfield, 1999).

The World Health Organization (WHO) included five occupational risk factors in its comparative risk assessment providing a unified framework of 26 major health risk factors contributing to the overall global burden of disease and injury (Jamison et al., 2006; Ezzati et al., 2002). The included outcomes were those for which WHO had rates of disease or injury for all regions calculated by International Classification of Disease codes. The WHO, the International Labour Organization and the European Union have provided the most current picture, yet still incomplete, of the overall problem of occupational health risks (Jamison et al., 2006; Ezzati et al., 2002; EC. 2000; Karjalainen and Niederlaender, 2001; Eurostat, 2010). To protect workers’ health from the adverse effects of vibration exposure, in 2002 the European Parliament issued the 2002/44/EC Directive (EC, 2002), which sets the minimum requirements to protect workers from the health and the safety risks arising from the exposure to mechanical vibrations. It was pointed out that
vibrations’ outcome can range from temporary but remarkable discomfort (e.g. carsickness), in case of frequencies lower than 2 Hz, to severe diseases in case of long term exposure to vibrations ranging from 2 to 20 Hz (Okunribido et al., 2006; Chiang and Liang, 2006; Seidel and Heide, 1986). As a matter of fact, in a survey on 1155 tractor drivers, tractor vibration and/or incorrect posture in driving activities were pointed out to cause more than 80% of the interviewed to suffer from low back disorders (Bovenzi and Betta, 1994); moreover, many research activities have been carried out in order to develop effective devices to mitigate vibration transmission to drivers (Saha et al., 2014; Pazooki et al., 2011; Braghin et al., 2009). The presence of such problems in both developed and developing countries, gives reason of the adequate attention ergonomics of agricultural operations deserves as well (Bishu et al., 1989).

This study reports on the results obtained assessing agricultural surface unevenness and the relevant tractor and operator’s responses: surface profiles were assessed replicating in controlled conditions (four poster test bench) the accelerations acquired running a tractor on different tracks at different speeds, tire pressures and ballast settings. The frequency range of the solicitations originating from the different surfaces was studied pointing out that, among all the recorded frequencies, only a few can be effective for surface characterization.

After outlining the state of the art, the paper describes: i) the used instruments and facilities; ii) the theory to replicate the acquired accelerations at the four poster test bench and to define operator WBW exposure; iii) the results of such methodologies in identifying the ground input and iv) its correlation with tractor and operator’s dynamics.

2 State of the Art
For several years, agricultural tractors tires have been the main mechanical vibration mitigation device relying, for their effectiveness, on eccentricity, load, resonance frequency, and elasticity characteristics: most of the studies have been focused on tires’ properties, dumping systems as well as their interaction (Pacejka, 2010; Taylor et al., 2000; Previati et al., 2007; Wille et al., 2005). Terrain irregularity and forward speed are the most important sources of vibrations (Scarlett et al., 2007; Nguyen and Inaba, 2011; Deboli et al., 2012) resulting in driver/operator work quality impairment (Bisaglia et al., 2006; Cutini et al., 2012) with consequent minor effectiveness and productivity.

The ISO 8608:1995 (ISO, 1995) describes an uniform method of reporting measured vertical surface profile data: it takes into account also off road terrain and indicates a correlation between ground input (profile roughness) and mechanical failure or operator’s discomfort (ISO, 1995; Roman et al., 2014; Agostinacchio et al., 2013). In such standard, surface profile measurement methods and instruments are not reported, confirming the difficulties for its proper measurement (Park et al., 2004; González et al., 2008). Surface profile measurements (e.g. obtained with optical technology) do not have the required precision and repeatability as they do not account for soil profile deformations induced the by machine traffic itself (Fassbender et al., 1997). The same ISO 8608 recommends care for off-road measurements both for soft surfaces (flattered and filtered by wheel forwarding) and hard surfaces (because of the filtering effect of the wheel envelopment).

One existing approach to this topic consists in an iterative methodology based on signal acquisitions from tested vehicles followed by test bench replications: i.e. accelerations are acquired at specific parts of the vehicle (usually at the hubs) during the testing in operative conditions; afterwards the machine is placed on a test bench whose actuators are driven to create, by deconvolution method, the same input signals obtained in the former phase (Bisaglia et al., 2006; Anthonis et al., 2007).
3 Material and methods

3.1 Vehicle, sensors and test tracks

Acceleration acquisitions were carried out using one medium-range tractor equipped with: i) four-wheel drive transmission; ii) 89 kW rated power engine; iii) closed rubber mounted cabin; iv) mechanical suspended seat. To acquire accelerations the tractor was equipped with:

- four piezo-electric monoaxial accelerometers (range ±50 g, sensitivity 100 mV/g) to measure wheel hubs vertical acceleration;
- one triaxial seat accelerometer (range ± 50 g, sensitivity 100 mV/g) placed in correspondence of the seat surface to evaluate operator comfort.

The tractor was run in different operating conditions (Tab. 1) on two kind of testing surfaces:

a) ISO 5008:2002 test track (smooth track): this track, located at CNR-IMAMOTER facility (Turin, Italy), is 100 m long and made of two different parallel non-deformable lanes (left and right). It is made of wooden beams 80 mm wide and 80 mm spaced with different standardized heights (20 to 160 mm) to induce vibrations.

b) Terrain test benches: such tracks, located at the CREA Laboratory of Treviglio, are open field tracks whose soil is classified as Haplic Luvisol (typical soil of the west-northern parts of Italy –ESDC, 2005). Topsoil and subsurface are constituted by 68% sand, 24% silt and 8% clay. Table 1 and Figure 1 report the characteristics and the visual description of such test benches.

3.2 The Four Poster Test Bench

The four-poster test bench (Fig. 2) is located at the CREA Laboratory of Treviglio. It is made of:

- one self-leveling seismic mass (408 t of weight) isolated from the ground by means of 14 pneumatic air-springs;
- four servo-hydraulic articulated actuators for wheel-base/track adjustment on the seismic mass: they support four vibrating plates upon which the tires of the vehicle are placed;
- one 500 kWe powered hydraulic system and one control unit including one computer-based controller and one data acquisition unit.

The position of each actuator (up to the frequency of 100 Hz and a peak-to-peak amplitude of 250 mm) is controlled via computer to excite each tire of the vehicle in the vertical direction in order to reproduce the surface profiles in terms of vertical input of the surfaces. Four linear variable differential
transformer transducers measure actuators’ displacements to record the data for the subsequent processing.

### 3.3 Experimental plan and statistical analysis

ISO test track acquisitions (surface code = 5008) were performed with the tractor set up in ballasted (B) - and unballasted (N) conditions, with two tire inflation pressures (80 and 160 kPa) and four different forward speeds representing 16 operating conditions (Table 1). On terrain test benches (surface code = S1, S2 and S3), the tractor was run only without the ballast, with tires inflated at 160 kPa and at five or three different forward speeds representative of 13 operating conditions: on the whole 29 operating conditions have been obtained to be afterwards replicated at the four poster test bench (Table 1).

During the tests, accelerations on X, Y and Z axes were acquired at the rate of 1250 Hz by the accelerometers placed at the seat and on Z axis at each of the hubs for a whole of 7 channels: each setting was replicated three times for a whole of 609 measurements. Accelerations acquired at tractor’s seat were used to assess the comfort value while accelerations acquired at the hubs of the tractor were afterwards reproduced on the four hydraulic actuators test bench at CREA laboratory.

To increase the knowledge attained from the considered variables and, according to them, trying to discriminate as much differences as possible, the 29 spectra of actuator plates displacements reproducing the all test tracks (in frequency domain) were processed by means of principal component analysis (PCA) using MiniTab statistical software (Minitab, 2010). PCA is a linear, unsupervised pattern-recognition technique that analyses, classifies and reduces the dimensionality of numerical datasets in multivariate problems (Todeschini, 1998); it allows the extraction of target information from the dataset, the analysis of its structure and global correlation of the variables. Moreover, to better compare the solicitations originating from ISO and Terrain test benches, data related to the runs performed in unballasted conditions and with tires inflated at 160 kPa underwent further PCA analysis followed by “Varimax” axis rotation according to the extracted coefficients (rotation of the original factors in such a way that the variance of the loadings is maximized - Kaiser, 1958).

### 3.4 Theory/Calculation

#### 3.4.1 The Drive Signal

The four poster test bench, with the vertical displacement of its actuators, reproduces the same acceleration acquired at the hubs during the field tests (Figure 3). To do this, the so called “drive signal” (reproducing the profile of the surfaces acquired at the passage of the tractor) needs to be calculated for each actuator by means of iterative Deconvolution (ID) procedure (ISO, 2002).

ID is a computerized control technique enabling the replication, in laboratory conditions, of vehicle or component responses previously measured during the field tests. ID is an off-line iterative feed forward procedure according to which actuator drive signals are updated on the base of: a) the measured frequency response function (FRF) matrix of the test arrangement; b) the tracking errors obtained during the previous iterations. During laboratory tests the Remote Parameter Control (RPC®) software from MTS Systems Corporation (Eden Prairie, Minnesota, USA) was used to obtain the drive signals representing the profile of the surfaces at the passage of the tractor. The whole process is made of six steps:
a) **Vehicle dynamics data record:** transducers, placed on the vehicle, measure its accelerations recording data in either analog or digital format. In this case the signals recorded were the four accelerations of the tractor’s hubs (see 3.1).

b) **Data transfer to the personal computer.** After being recorded, data are digitized and transferred to a MS Windows® based computer for preliminary editing and processing to obtain the hub accelerations to be reproduced (Desired Signal).

c) **Measurement of the system Frequency Response Function (FRF).**

To calculate the displacement of the actuators that will reproduce the signals recorded at the hubs, at first the tractor is placed on the four poster test bench moving each plate (one at a time) with random signal and acquiring the responses at the four hubs: the outcome is a 4x4 transfer matrix (TM) containing 16 FRFs. The generated random drive signal is used to drive the test system: as a matter of fact measuring the tractor’s responses allows the creation of the system model of the tractor that is subsequently used to calibrate the system model (FRF-1) allowing the definition of actuator’s displacements.

d) **Calculation of the initial drive signal.** The system model created in the previous step and the desired response time history (from step “b”) are processed to create the estimation of the initial drive signal.

e) **Iterations performing.** The tested system is nonlinear and it may have inherent cross couplings: because of this, data processing iteratively measures the deviations between the actual and the desired time history responses (meant as the sequence of the accelerations tractor hubs are subjected to) to accordingly correct (by means of a gain) the drive files subsequently generated. Iterations are performed until a suitable drive signal (the one inducing the desired response in the tested tractor) is achieved (equation. 1).

\[
\text{Drive Signal} = \text{Desired Signal} \cdot \text{FRF}^{-1} \cdot \text{gain}
\]  

(1)

Where \(0 < \text{gain} < 1\)

To evaluate the error of the reproduced acceleration signal the normalized root mean square error (NRMSE) of the error signal between the desired and the achieved responses calculated for each iteration, was considered (eq. 2). It is defined as:
Filtered Error = difference between the desired signal and the response signal

Response signal = signal currently reproduced by the four poster test bench)

Vehicle testing. Once the suitable drive signals are obtained, they are used as command input to perform vehicle tests on the bench.

To better understand such profile reproduction process, the physics of tyre responses to road unevenness needs to be considered as well. As a matter of fact, the outcome of any tyre running at constant speed over a cleat, whose length is much smaller than the contact length, involves the consideration of the following elements (Pacejka, 2010; Jianmin et al., 2001):

- tyre envelopment properties (variations in vertical and longitudinal forces as well as in the angular velocity of the wheel);
- effective road plane (the effective height and slope of a short trapezoidal cleat is approximated at the axle by a half sine wave);
- effective rolling radius when rolling over a cleat (increment in normal load, local forward slope, local forward curvature);
- the fact that the reproduction in laboratory is purely vertical while on the test track there is a sum of vertical and longitudinal components.

As a matter of fact, the displacement recorded at the hub of a rolling tire, because both of the rolling and of the radial deflection occurring as consequence of the passage over the cleat (Figure 4, on the left), is ascribable to a sine wave. As consequence, the displacement of the test bench actuator simulating the effect of the cleat shall result in a sine function too (Figure 4, on the right).

### 3.5 Comfort of the Operator

The ISO 2631:1997 testing standard (ISO, 1997) was used to assess operator exposure to vibration: in accordance with it, vibration assessment requires the calculation [Eq. 3] of the weighted and gained root-mean-square (RMS) acceleration \( \alpha_{W} \) along the three axes \( i = x, y, z \):

\[
\alpha_{W} = k_{(x,y,z)} \sqrt{\sum_{i=1}^{n} (W_{i} \cdot \alpha_{i})^2}
\]  

where:
\( k_{i(x,y,z)} \) is a multiplying factor, set at 1.4 for \( x \) and \( y \) axes and 1 for \( z \) axis.

\( W_i \) is a weighting factor given by the standard itself.

\( a_i \) is the acceleration acquired at the seat (m \( s^{-2} \)).

The calculated \( a_i \) were subsequently used to define whole body vibration (WBV) risk conditions according to 2002/44/CEE European directive (EC, 2002) that, adopting an exposure of 8 hours per day, identifies the following classes:

- \( a_i < 0.5 \) m \( s^{-2} \): no risk (comfortable conditions)
- \( 0.5 < a_i < 1 \) m \( s^{-2} \): subject to risk of vibration (uncomfortable conditions)
- \( 1 < a_i < 1.5 \) m \( s^{-2} \): maximum time of exposure needs to be calculated (very uncomfortable conditions)
- \( a_i > 1.5 \) m \( s^{-2} \): dangerous situation, working activity is not allowed

WBV have been studied also in the frequency domain by processing the data according to multivariate analysis (PCA) and extracting the first and the second principal components.

4 Results and Discussion

The vertical accelerations acquisitions at the hubs showed that the frequencies characterizing vehicle and operator dynamics ranged between 0.6 and 12 Hz as already pointed out by literature (Braghin et al., 2008 and 2009); Data processing pointed out also that the roughness characterizing the profile of the testing surfaces was such that the effect of engine rotation and of tires’ lugs on operator could be considered negligible (Figure 5). Starting from these considerations, data processing focused the frequency domains (spectra) of operator’s comfort (considering the frequencies ranging between 0.0 and 80 Hz in compliance with ISO 2631 standard (ISO, 1997) and of surface profiles obtained by actuator displacements (in the 0.0 - 20 Hz range) of the four poster test bench.

4.1 Comfort of the Operator

Weighted RMS acceleration values were found ranging from 0.29 m \( s^{-2} \) (x axis) to 1.85 m \( s^{-2} \) (z axis) at varying of the test settings: such data are displayed in Table 2 with a built-in grey scale of colours indicating operator safety conditions. Data processing pointed out that \( a_i \) is correlated to tractor speed: in particular runs carried out on the ISO track at 3.33 and 3.89 m/s\(^{-1}\) with tires inflated at 160 kPa were found out to be the most uncomfortable ones both in ballasted and unballasted conditions.

The results of multivariate data processing of the spectra are reported in table 3. With reference to the ISO test track the percentages of explained variance (Wold et al., 1987) for \( x \), \( y \) and \( z \) axes are 75\%, 74\% and 92\% while, in the case of the tests carried out on terrain test benches, such percentages are 78\%, 67\% and 87\%. The frequencies characterizing operator’s comfort the most, in all the considered benches and test settings, turned out all to be in a restricted range of values (0.8 to 3.1 Hz): being such frequencies already known in literature (Nguyen and Inaba, 2011; Deboli et al., 2012), the attention was focused on the issue that a small range of frequencies could be sufficient to address the overall vehicle dynamic.
It turns out an high amplitude of the low frequencies (mainly between 0.6 and 0.8 Hz) that, anyway, are not connected to high acceleration values. This energy was present only on the y axis (Table 3) showing that this is the outcome of the roll of the vehicle. This is the reason why the y axis acceleration values at the operator are significant for comfort and safety but of the same order of magnitude of the x and z axes, mainly characterized by the 1.8 – 3.0 Hz.

4.2 The reproduction of the test track profile in laboratory

4.2.1 Model of the vehicle

TM maximum amplification peaks are in the range between 2.5 - 3 Hz that corresponds to tire resonance. As expected, the value of the resonance frequency increased with tire stiffness, depending on the inflation pressure, and decreased with load (ballasted conditions). Other peaks were found at about 7 - 8 Hz: they indicated the resonance of the cab due to rubber mount supports. This can be deduced from Figure 6 showing the outcome of the TM from the rear plates to the rear hub only: the amplification recorded in any setting (g \cdot mm^{-1}) increases at increasing values of frequency (Hz) being plate displacement (mm) the TM input and the acceleration at the hub (g) the related output.

With reference to tires’ elastic properties (Table 4), data processing pointed out a difference of the resonance frequency values between dynamic (ISO track) and static conditions (four poster test bench) confirming what had been previously pointed out in literature: when tire starts rolling it’s stiffness decreases, from 10% to 26%, becoming stable and independent from the speed (Pacejka, 2010; Jianmin et al., 2001; Soderling et al., 1999; Wong, 2008).

4.2.2 Simulation

Once the model of the vehicle has been obtained (see chapter 3.4.1), calculus iterations were performed: the resulting average RMSE of 0.2 indicated an adequate reproduction level of the drive signal so that desired and response signals basically overlapped (Figure 7 a, b).

When the signal is reproduced at the four poster test bench, the RMS (mm) of vertical plate displacements changes at varying of the solicitations to be reproduced: data presented in table 5 show that increasing the speed during the acquisition runs originates solicitations that, to be successfully reproduced, give rise to increasing RMS of plate displacements as well; on the other hand, when acquisition runs have been performed at increasing tire stiffness (and machine weight as well), the same RMS decreases. Regardless of the kind of surface (ISO or Terrain), the combination of profile roughness and forward speed induces an increase of the spectrum magnitude in the whole considered range of frequencies.

With reference to frequency domain, actuators displacements, simulating the tractor vertical shifts induced by the profile of all the test tracks, were found to be enhanced and characterized by the elastic components of the vehicle (tires, cab rubber mounts, etc.). The spectral analysis of the reproduced profiles (Figure 8) shows that:

- in every test there is an energy peak (at about 3 Hz), correlated to the elastic properties of the tires, proportional to the forward tractor speed in terms of amplitude;
- in every test, there are energy peaks (at about 6 - 7 Hz) corresponding to the vibration modes of the cabin.
As consequence, it can be deduced that, no matter the forward speed, all the considered surfaces show similar frequency spectra shapes with more relevant amplitudes at frequencies lower than 3 Hz while, in case of frequencies higher than 12 Hz, spectral components turn out to be negligible. This means that, with reference to agricultural tractors, the displacement of the test bench actuators simulating the ground input results in frequencies typical of the resonance of the vehicle and/or its components that are similar to those previously pointed out studying the operator’s comfort and the accelerations at the hubs (see Table 3 and Figure 5). According to this, it can be stated that, no matter the randomness of the test track profile, the accelerations resulting from ground inputs (vertical solicitations induced by profile roughness) are characterized by the elastic properties of the tractor (tires above all). A similar trend can be noticed in previous studies aimed at verifying only the factual reproducibility of the acquired solicitations by means of four poster test bench on agricultural tractors (Bisaglia et al., 2006; Anthonis et al., 2007; Cutini et al., 2013) as well as agricultural implements (Cutini and Bisaglia, 2013).

4.3 Analysis of the Reproduced Surface Profiles

The data processing of plate displacements (mm) reproducing the solicitations acquired with the N_160 setting showed that, at varying of the reproduced frequencies, the variances of those related to the Standard Test Track were one order of magnitude higher than those related to Grass, Soil and Stones surfaces. Moreover, it was pointed out (and confirmed) that, no matter the surface, the highest variances were those associated with vibrations ranging from 0.2 Hz to 3.4 Hz.

To better compare the different surfaces, the PCA was subsequently performed using as reference the N_160 setting and focusing the plate displacement recordings related to the 0 - 3.4 Hz range of frequencies. According to this multivariate processing, the 1st principal component (PC 1) has variance 12.053 mm and represents 67% of the total variance; the 2nd principal component (PC 2) has variance 2.371 mm and represents 13.2% of the total variance. Overall both the components account up to 80.1% of the total variance and the two PCs model was found not to present outliers. Despite this, the analysis of the loadings could not help identifying clearly the latent variables describing the found PCs. Therefore, further factor analysis with axes rotation (Varimax rotation method) was carried using the coefficients from the PCA.

According to the rotated solution of the loading plot (Figure 9, above), it can be noticed that the frequencies ranging from 0.2 to 0.8 Hz are those more intensely characterizing the rotated PC 1 while those ranging from 2.8 to 3.4 Hz mainly characterize the rotated PC 2. The resulting score plot (Figure 9, below) shows that: i) differences between the various surfaces run with the tractor are mainly explained by the 2nd rotated PC; ii) solicitations originating from the standard test track are mainly described by vibrations ranging from 0.2 to 1.2 Hz; iii) vibrations ranging from 2.8 to 3.4 Hz mainly characterize the observations acquired from the front axis of the tractor when it had been run at higher speed on tilled soil, grass and stones. This is consistent with the fact that front tires where those subjected to higher displacements; iv) 1 to 1.8 Hz vibrations tend to characterize the acquisitions from the rear hubs when tractor had been run at low/moderate speeds.

Considering the frequency bandwidth mainly affecting operator’s comfort (1.8 – 3.0 Hz), the amplitude of plate displacements reproducing the surface profiles was found to change considerably at varying of the tractor setting. In particular, the highest values of plate displacements were those obtained for B_80 settings while the lowest for the N_160 settings. This can be ascribed to tire properties at the different pressure and mass setting: as a matter of fact, in N_160 configuration tires have greater stiffness (than “_80” settings) and lower mass (than “B_” settings), so less cylinder displacement is enough to
reproduce solicitation. The highest plate displacements is related to the most comfortable settings (B_80) while the lowest the most uncomfortable one (N_160).

5 Conclusions
Running one agricultural tractor on smooth ISO test track and three different agricultural surfaces (grass, soil and stones) at different forward speeds, and reproducing the same working environment by means of one four-poster test bench, allowed obtaining twenty-nine profiles’ spectra that showed similar shape in terms of frequency. Consequently, as solicitations originating from agricultural surfaces, no matter the surface profile, have been shown to belong to a specific range (1.8 to 3.0 Hz), a remarkable simplification and standardization of tractors’ dynamics, comfort and materials resistance testing activity can be introduced (e.g. developing a rough test surface to be run at a forward speed enabling vehicle dynamic, comfort and material solicitation excitation).

5.1 Acknowledgements
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## 7 Tables

Table 1: layout of the experimental plan. The test settings codes reported in the text can be obtained assembling surface code and tractor set up options (e.g. 5008_N_80_6)

<table>
<thead>
<tr>
<th>Surface Code</th>
<th>Description</th>
<th>Surface characteristics</th>
<th>Tractor set up options</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Moisture $^a$ Penetration resistance $^b$</td>
<td>Ballast settings $^c$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(%) (MPa)</td>
<td>(kPa) (km h$^{-1}$)</td>
</tr>
<tr>
<td>5008</td>
<td>Standard test track (Figure 1, a)</td>
<td>- -</td>
<td>N; B</td>
</tr>
<tr>
<td>S1</td>
<td>Tilled soil (Figure 1, b)</td>
<td>15.0 2.9</td>
<td>N</td>
</tr>
<tr>
<td>S2</td>
<td>Soil covered with grass (Figure 1, c)</td>
<td>13.1 5.3</td>
<td>N</td>
</tr>
<tr>
<td>S3</td>
<td>Soil with high skeleton percentage (Figure 1, d)</td>
<td>13.5 Not available</td>
<td>N</td>
</tr>
</tbody>
</table>

$^a$ According to MiPAF (1999) [45]  
$^b$ According to ASAE (1999) and ASAE (2004)  
$^c$ N = without ballast; B = with ballast
<table>
<thead>
<tr>
<th>Track Condition (expressed as setting code)</th>
<th>Weighted RMS accelerations in the three axes (m s⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
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<tr>
<td>S1_N_160_5</td>
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<td>S1_N_160_7</td>
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<tr>
<td>S3_N_160_5</td>
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<tr>
<td>5008_N_80_6</td>
<td>0.36</td>
</tr>
<tr>
<td>5008_N_80_10</td>
<td>0.71</td>
</tr>
<tr>
<td>5008_N_80_12</td>
<td>0.68</td>
</tr>
<tr>
<td>5008_N_80_14</td>
<td>0.98</td>
</tr>
<tr>
<td>5008_N_160_6</td>
<td>0.53</td>
</tr>
<tr>
<td>5008_N_160_10</td>
<td>0.75</td>
</tr>
<tr>
<td>5008_N_160_12</td>
<td>1.05</td>
</tr>
<tr>
<td>5008_N_160_14</td>
<td>1.0</td>
</tr>
<tr>
<td>5008_B_80_6</td>
<td>0.29</td>
</tr>
<tr>
<td>5008_B_80_10</td>
<td>0.89</td>
</tr>
<tr>
<td>5008_B_80_12</td>
<td>0.69</td>
</tr>
<tr>
<td>5008_B_80_14</td>
<td>0.57</td>
</tr>
<tr>
<td>5008_B_160_6</td>
<td>0.52</td>
</tr>
<tr>
<td>5008_B_160_10</td>
<td>0.95</td>
</tr>
<tr>
<td>5008_B_160_12</td>
<td>1.37</td>
</tr>
<tr>
<td>5008_B_160_14</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Comfortable
Subject to risk of vibration

Maximum time of exposure to be calculated

Working activity not allowed

See Tab. 1 for the meaning of the surface, ballast, tire inflation and speed codes
### Table 3: Percentages of explained variance with the related main frequencies ranges.

<table>
<thead>
<tr>
<th>Axis</th>
<th>PC</th>
<th>Explained variance (%)</th>
<th>Main frequency range (Hz)</th>
<th>Explained variance (%)</th>
<th>Main frequency range (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x (longitudinal)</td>
<td>1</td>
<td>58</td>
<td>1.7 – 2.5</td>
<td>50</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>17</td>
<td>2.5 – 3.1</td>
<td>50</td>
<td>17</td>
</tr>
<tr>
<td>y (transversal)</td>
<td>1</td>
<td>53</td>
<td>0.8 – 1.2</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>21</td>
<td>1.1 – 1.5</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>z (vertical)</td>
<td>1</td>
<td>79</td>
<td>2.3 – 2.9</td>
<td>67</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>13</td>
<td>2.3 – 2.6</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Global</td>
<td>1</td>
<td>56</td>
<td>2.3 – 3.0</td>
<td>69</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>16</td>
<td>1.6 – 2.4</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

### Table 4: Frequency values (Hz) corresponding to tire resonance obtained in both dynamic and static conditions.

<table>
<thead>
<tr>
<th>Testing condition</th>
<th>Tractor axle</th>
<th>Tractor settings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without ballast</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 kPa</td>
</tr>
<tr>
<td>Four poster test bench</td>
<td>Front</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Rear</td>
<td>3</td>
</tr>
<tr>
<td>ISO Track</td>
<td>Front</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Rear</td>
<td>2</td>
</tr>
</tbody>
</table>

### Table 5: RMS amplitude of plates displacement (mm) reproducing tractor runs on ISO test track.

<table>
<thead>
<tr>
<th>Tractor settings</th>
<th>Forward speed (ms⁻¹)</th>
<th>Plates displacement RMS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tire Pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N 80 kPa</td>
<td>Front</td>
<td>1.67 2.78 3.33 3.89</td>
</tr>
<tr>
<td>80 kPa</td>
<td>8.1 13.6 15.7 18.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Front</td>
<td>Rear</td>
</tr>
<tr>
<td>----</td>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>N</td>
<td>160 kPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Front</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>80 kPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Front</td>
</tr>
<tr>
<td>B</td>
<td>160 kPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Front</td>
</tr>
</tbody>
</table>
8 Figures

Figure 1: Representations of the four surfaces adopted for the trials. a) ISO 5008 standard track; b) Tilled soil; c) Soil covered with grass; d) Soil with high skeleton percentage.

Figure 2: The four poster test bench (the shown agricultural tractor is meant just as example).
Figure 3: Graphical representation of the ID method for data acquisition in field conditions (ISO track) and their replication in controlled conditions (four poster bench) to obtain the actuators’ vertical displacement reproducing the test track.
Figure 4: graphical representation of the simulation of the vertical effect of a square cleat on a tire; the displacement of the actuator simulating the cleat is a sine wave.

Figure 5: Example of the spectra of the vertical accelerations acquired on the front left hub (FR), as explained in the text, frequencies above 12 Hz can be considered as “white noise”.
Figure 6: Output of the transfer matrix from one of the rear plates (mm) to the corresponding rear (R) hub at different ballast (N and B) and inflation pressure (80 kPa and 160 kPa) conditions.
Figure 7: Level of reproducibility of the desired signal in Laboratory (taking 5008_N_160_12 as example) both in frequency (7a) and in time (7b) domains.
Figure 8: Spectra of the settings N_160 on the front axle (F). Shaded areas refer to the similar trends obtained on any kind of surface.
Figure 9: Rotated solution of the Loading plot (above) and of the Score plot (below) of the multivariate analysis performed on plate displacements reproducing the vibrations acquired with the N_160 setting. In the score plot, for any considered surface, observation labels are represented by tractor forwarding speed (km/h) and ballast position (either front or rear).