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VIBRATION EXPOSURE ON FORK-LIFT TRUCKS

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Abstract—This study investigates the effects of the main characteristics of the working condition on the vibration exposure on fork-lift trucks. Four hundred and eighty recordings were made on five trucks equipped with four different types of tyres and a 'normal' or an 'anti-vibration' seat, driven while empty or loaded, on a smooth or a rough track by three workers. An analysis of variance was performed to study the main effects and the significant interactions between these factors. A mathematical model is proposed for the weighted acceleration on the floor and on the seat in the vertical axis. This shows quantitatively that the vibration exposure is mainly influenced by the roughness of the track, the speed and the quality of the seat. Inflated tyres are preferable when an anti-vibration seat with a very low resonance frequency is used. In other cases, cushion tyres are more indicated.

INTRODUCTION

Fork-lift trucks are quite common in the workplace and, in many industries, they represent the main sources of vibration exposure. It is estimated that in France 200 000 fork-lift trucks would be in use, the number of users being around 700 000 (Saint-Eve and Donati, 1993).

The order of magnitude of this exposure is known to vary greatly depending upon the type of truck, tyres, seat, the levelling of the track, the load, etc. But to our knowledge, no systematic study has even been conducted to study all the main effects and the interactions between these factors.

This paper presents the results of such a study on the most frequent small fork-lift trucks, less than 5 tons in nominal load. This research was particularly undertaken to compare the influence of cushion and inflated tyres, and to derive some guidelines to optimize the choice of the tyres as a function of the other characteristics of the exposure.

MATERIALS AND METHODS

The study was carried out for five different models of fork-lift trucks, four types of tyres, two types of seats, two types of track for three workers and while empty and loaded. The five models of trucks included three diesel trucks of 1.5, 2.5 and 4 tons and two electric trucks of 1.5 and 2 tons. The main technical characteristics of these trucks are given in Table 1.

Each truck was successively equipped with:
—soft cushion tyres in the front and in the rear;
—hard cushion tyres in the front and in the rear;
—inflated diagonal tyres in the front and in the rear;

Table 1. Technical characteristics of the five fork-lift trucks and the five types of tyres

	1.5-ton diesel TCM FD15Z15	2.5-ton diesel TCM FD25Z2S	4-ton diesel TCM FD40Z6	1.5-ton electric TCM FHB15H4	2-ton electric TCM FHB20H4
Nominal load	1000 kg	2000 kg	3000 kg	1000 kg	2000 kg
Centre of gravity	50 cm	50 cm	60 cm	50 cm	50 cm
Maximum speed					
—empty	14.5 km h^{-1}	19 km h^{-1}	19 km h^{-1}	16 km h^{-1}	16.5 km h^{-1}
—fully loaded	—	17.5 km h^{-1}	18 km h^{-1}	13.5 km h^{-1}	14.5 km h^{-1}
Total weight empty	2710 kg	3740 kg	6390 kg	2200 kg	2550 kg
Tyre dimensions					
—front	6.50 × 10	7.00 × 12	8.25 × 15	6.50 × 10	7.00 × 12
—rear	5.00 × 8	6.00 × 9	7.00 × 12	5.00 × 8	6.00 × 9
Types of tyres					
—cushion soft	B. Elite	B. Elite	S. SRS	S. SRS	B. Elite
—cushion hard	S. ECR	S. ERS	B. ConfortE	B. ConfortE	S. SRS
Inflated diagonal	Bridgestone	Bridgestone	Bridgestone	Bridgestone	Bridgestone
Inflated radial	—	Continental 1C80 extra deep	—	—	Continental 1C80 extra deep

B = Bergougnan.
S = Solideal.

—a combination of hard cushion tyres in the rear and inflated diagonal tyres in the front.

Additional tests were made with inflated radial tyres in the front and in the rear on two trucks only: the 2-ton electric and the 2.5-ton diesel.

Two types of seats were tested on each truck:

—a EBLO 1050 FE seat without anti-vibration system;

—a EBLO 1040 FE seat with a mechanical anti-vibration suspension. This seat was adjusted according to the weight of the driver.

The tests were performed on two different tracks aiming at representing the extremes in ground roughness that could be met in industry:

—a track of 300 m on a very rough paved track;

—a track of 280 m on a very smooth concrete ground.

Tests were conducted without any load and while carrying the nominal load. Three drivers were chosen at random in the company. They were skilled in the driving of all fork-lift trucks and were instructed to drive 'as usual'.

All arrangements of the six factors were tested and therefore 480 tests were performed. For the radial tyres, 48 additional tests were performed.

Vibration was recorded using two triaxial accelerometers, one mounted in the normalized pad (B & K 4322) placed on the seat, the other (B & K 4321) placed using a magnet, on the floor, next to the seat. Both were oriented according to ISO standard 2631 (1978). The X, Y and Z signals on the seat were recorded using a B & K 2231 sound level meter equipped with the B & K BZ7105 and 2522 modules for the measurement of vibration (dynamic range better than 60 dB and frequency response from 1 to 80 Hz).

On the floor, vibration was recorded only in the X and Z axes using B & K 2634 pre-amplifiers. The signals were recorded on an 8-channel TEAC RD111T DAT recorder (dynamic range greater than 70 dB and frequency response from 0 to 5000 Hz).

The five signals were digitized at a frequency rate of 256 points per s using an IBM PS2/80 computer equipped with an acquisition card National Instruments MC-MIO-16L. Anti-aliasing low pass filters were used with a cut-off frequency of 90 Hz before the digitization. The numerical treatment of the data made possible to compute for each axis 'i', the equivalent weighted RMS value of acceleration (a_{iw}) as well as the one-third octave band spectrum of the weighted RMS acceleration for each test.

Two statistical analyses were performed: first an analysis of variance of a_{Zws} (the weighted equivalent acceleration in the Z axis on the seat) and of a_{Zwf} (on the floor), aiming at studying the main effects of each factor, as well as the interactions between these factors. Second, a multiple correlation analysis aiming at developing a mathematical model that could be used to predict the average acceleration in a given working situation as well as determining the most appropriate ways to lower the exposure level.

RESULTS

Table 2 provides the means, standard deviations, minima and maxima of the weighted equivalent acceleration in the three axes on the seat and in the axes X and Z on the floor, for all the experiments.

The vibration acceleration is clearly much greater in the vertical axis than in the X and Y axes, both on the seat and on the floor and limit values such as those proposed by ISO standard 2631 (1978) or BS-standard 6841 (1987) are exceeded in this axis. Therefore, for the sake of simplicity, the analyses hereunder will be limited to this Z axis.

ANOVA analysis: main effects

Table 3 gives the average a_{Zw} values on the seat and on the floor, for all the main effects. The mean driving velocity is also given. These main effects were in all cases significant at the 0.1% level, except for the truck effect significant only at the 5% level.

Driver effect

The accelerations on the seat are the greatest for the worker weighing only 55 kg and driving fast, while they are the smallest for the heaviest one, driving more slowly.

Table 2. Means, standard deviations, minima and maxima of the weighted equivalent accelerations per axis on the seat and on the floor

	Mean ($m\ s^{-2}$)	SD ($m\ s^{-2}$)	Minimum ($m\ s^{-2}$)	Maximum ($m\ s^{-2}$)
Seat				
a_{Xw}	0.53	0.20	0.20	1.10
a_{Yw}	0.41	0.11	0.22	0.89
a_{Zw}	1.59	0.67	0.39	3.80
Floor				
a_{Xw}	0.43	0.25	0.15	4.12
a_{Zw}	1.77	0.69	0.65	5.19

Table 3. Average weighted acceleration in the vertical Z axis, on the seat and on the floor, and mean driving speed for all the main effects

	Driving speed (km h^{-1})	Seat a_{Zw} (m s^{-2})	Floor a_{Zw} (m s^{-2})
Worker (weight)			
1 (72 kg)	11.2	1.46	1.68
2 (55 kg)	12.1	1.77	1.84
3 (72 kg)	12.2	1.55	1.78
Load			
—empty	12.7	1.68	1.98
—loaded	11.0	1.51	1.55
Track			
—concrete	12.4	1.18	1.26
—paved	11.2	2.01	2.27
Truck			
—1.5-ton diesel (2710 kg)	11.8	1.57	1.88
—2.5-ton diesel (3740 kg)	12.4	1.59	1.90
—4-ton diesel (6390 kg)	12.4	1.69	1.82
—1.5-ton electric (2200 kg)	11.3	1.58	1.66
—2-ton electric (2550 kg)	11.4	1.54	1.57
Seat			
—normal	11.8	1.90	1.77
—anti-vibration	11.8	1.29	
Tyre			
—soft cushion	12.1	1.56	1.82
—hard cushion	11.7	1.50	1.80
—diagonal inflated	11.6	1.78	1.58
—mixed	11.9	1.54	1.87
—radial inflated	12.8	1.76	1.78

The weight effect is very likely as it contributes to decrease the resonance frequency of the suspensions of both the seat and the truck and therefore, to increase the attenuation of vibration at higher frequencies.

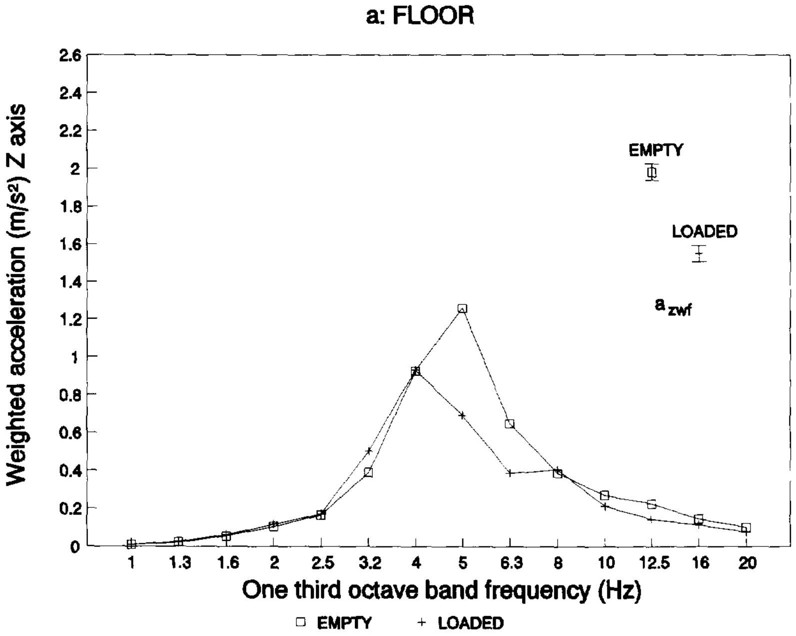
These postulated weight and speed effects seem to play a role also for the acceleration on the floor, however to a lesser extent.

Load effect

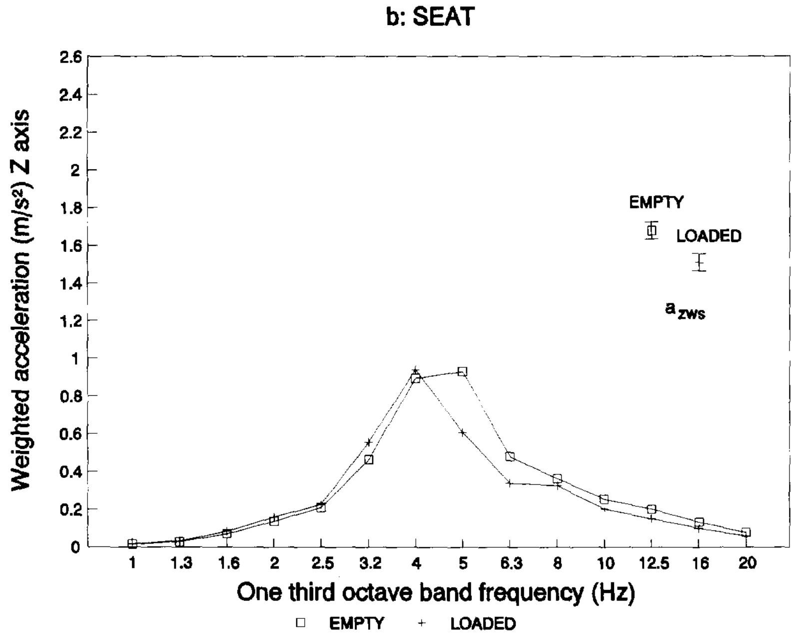
Accelerations are significantly greater with the truck unloaded, driven faster. Both the weight and speed effects play likely a role similar to the one described for the driver effect. Figure 1 gives the one-third octave spectra of a_{Zws} and a_{Zwf} in both conditions and clearly shows that the loading of the truck contributes to a significant lowering of the predominant one-third octave band and to reduced accelerations at frequencies above 4 Hz.

Track effect

The track effect is clearly the greatest of the effects since the difference between the acceleration on smooth concrete and on a rough paved tracks reaches 1 m s^{-2}, both on the seat and on the floor of the fork-lift truck. The one-third octave band analyses showed that, although the driving speed is reduced, the shape of the spectra remains the same with the predominant one-third octave bands centred at 4 and 5 Hz. It is worth noting that, on average, the accelerations are reduced by about



a: FLOOR



b: SEAT

Fig. 1. Average one-third octave band spectra of the weighted equivalent acceleration on (a) the floor and (b) the seat, in the vertical axis, without and with a load.

0.10 m s^{-2} on the seat in comparison with the floor on the concrete track and by 0.25 m s^{-2} on the paved track.

Truck type effect

On the floor, the weighted acceleration amplitudes are not statistically different between the three diesel trucks nor between the two electric ones. However, both groups differed slightly but significantly by about 0.2 m s^{-2}, the electric trucks vibrating less: this could be due to a reduced speed for these trucks or a smoother operation of the engine.

On the seat, on the contrary, the acceleration amplitudes are about the same for all five trucks. An increase, compared to the floor level, is observed for the 4-ton diesel and the two electrics, due to a significantly different behaviour of the two seats, as it will be shown in Fig. 4. The truck effect remains however small (0.1 m s^{-2}) compared to the other main effects.

Seat effect

Figure 2 shows the one-third octave band spectra of the weighted acceleration on the floor of the truck and on the seats both without and with anti-vibration system. The accelerations are clearly significantly greater, mainly in the one-third octave band centred at 4 Hz, with the 'normal' seat, while they are reduced, but above 4 Hz only, with the anti-vibration seat. The overall weighted amplitude is increased by some 7% in the first case and reduced by 27% in the second, the total difference between the two seats reaching 0.6 m s^{-2}. Analyses made in the X and Y axes (and not reported here) showed that the type of seat (at least with the model used) had no influence on the acceleration levels in these axes.

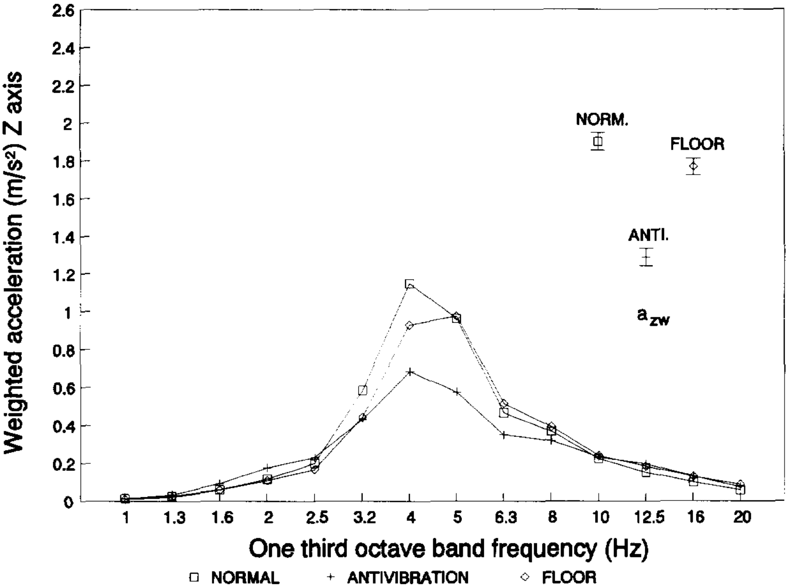


Fig. 2. Average one-third octave band spectra of the weighted equivalent acceleration in the vertical axis, on the floor and on the seat of the 'normal' seat and the anti-vibration seat.

Tyre effect

Figure 3 shows the one-third octave band spectra of the weighted acceleration on the floor and on the seat for the five types of tyres. On the floor the vibration amplitudes do not differ between the soft and hard cushion tyres. They tend to be smaller for the inflated tyres and especially for the diagonal types. Paradoxically, they are significantly greater with mixed tyres. The main difference between inflated and cushion tyres is the fact that the predominant one-third octave bands are centred at lower frequencies with the first type (3.2 and 4 Hz instead of 4–5 Hz).

On the seat, these spectral differences are again observed, the levels in the 3.2 Hz one-third octave band being increased due to the resonance of the seat and the levels in the 4 and 5 Hz bands being significantly decreased due to the attenuation of the seat. This clearly explains that the overall weighted accelerations are this time the greatest, by in average 0.24 m s^{-2}, for the inflated tyres. There exists obviously, as will be seen later, an interaction effect between the type of tyres and the type of seat, the situation being the worse with inflated tyres and a non suspended seat.

Interactions

Only first-order interactions were analysed and the results indicated significant interactions only between truck and track types, truck and tyre types and tyre and track types, as far as the vibration on the floor is concerned. On the seat, however, the significant interactions were restricted between truck and tyre types, truck and seat types, and seat and tyre types.

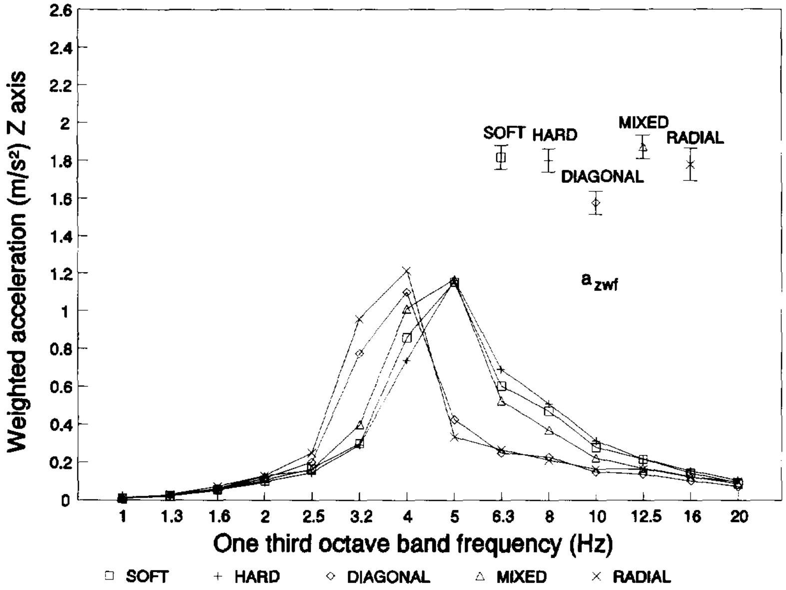
Most of the information carried by these interactions is illustrated by Fig. 4 showing the average weighted equivalent acceleration on the floor as well as on the two types of seats, on both types of track and for the five types of trucks and five types of tyres. In the absence of interactions, the effects of the track, the seats, the tyres and the trucks would be identical and all the lines would be parallel. Clearly, one major interaction appears between the diagonal tyres and the antivibration seat, combination for which the acceleration level increased drastically.

Regression analysis

Following the analyses of variance reported above, an attempt was made to derive a mathematical model that could be used to predict the average exposure acceleration as a function of the characteristics of the working condition of the fork-lift truck. This was done using a multiple correlation analysis with the equivalent weighted accelerations in the vertical axis on the seat or on the floor as the dependent variables and, as independent variables:

—a variable 'track', characteristic of the roughness of the road and being worth 0 on a smooth concrete track and 1 on a very rough paved track;
—a variable 'load', being equal to 0 without a load and 1 with the full nominal load;
—a variable 'seat', equal to 0 for a normal seat and 1 for a mechanically suspended antivibration seat;
—a variable 'truck', equal to 0 for diesel trucks and 1 for electric ones;

a: FLOOR



b: SEAT

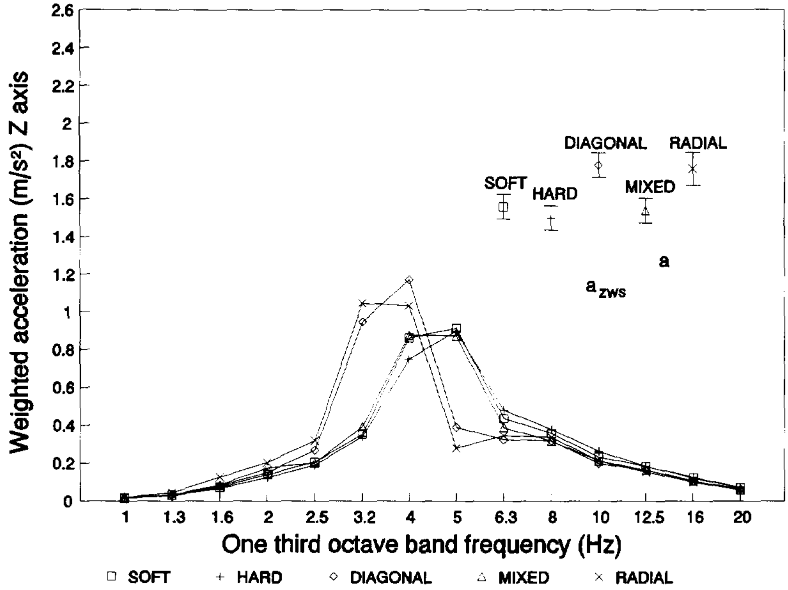


Fig. 3. Average one-third octave band spectra of the weighted equivalent acceleration on (a) the floor and (b) the seat, in the vertical axis, with the five different sets of tyres.

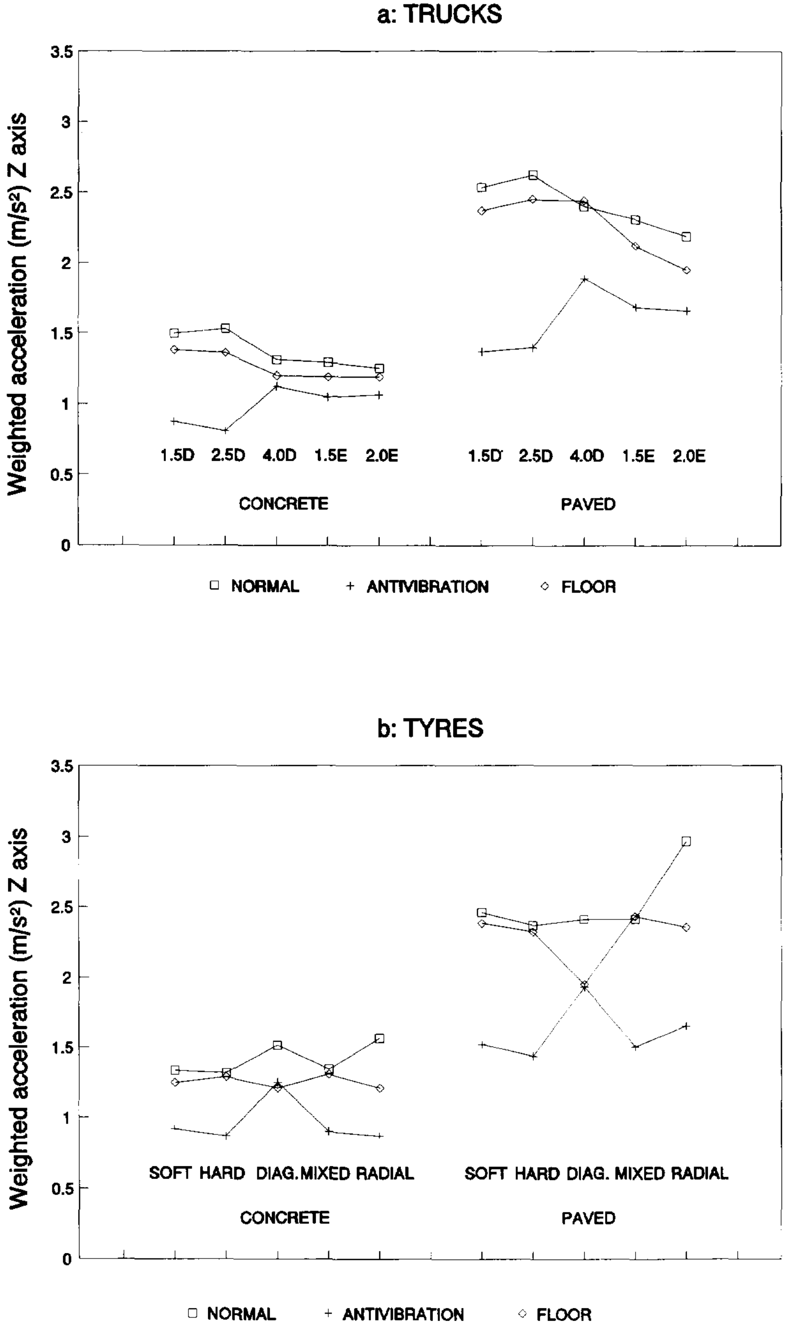


Fig. 4. Averages of the weighted equivalent acceleration in the vertical axis, on the floor and on the two types of seats, according to the nature of the track, for (a) the five different trucks and (b) the five different sets of tyres.

—a variable 'tyre', being worth 0 in case of cushion or mixed types and 1 for diagonal tyres; data with the radial tyres were not used in these models, as they were recorded on two trucks only;

—a variable 'weight', equal to the weight of the driver minus 70 kg and divided by 10;

—a variable 'speed', equal to the driving speed of the fork-lift truck in km h^{-1}.

Interactions between pairs of variables (except for weight and speed) were tested using their products. However seat × tyre, for instance, is equal to 1 only in the case when a suspended seat is used in conjunction with inflated tyres and equal to 0 in all other combinations. In order to test the other combinations, the products $(1-\text{seat})\times\text{tyre}$, $\text{seat}\times(1-\text{tyre})$, as well as $(1-\text{seat})\times(1-\text{tyre})$ were also tested. The same procedure was adopted for all dichotomic variables.

Table 4 gives the results of the multiple correlation analyses, with the interactions, while Table 5 gives the results with only the main effect of the variables. As far as the vertical acceleration on the seat is concerned and as noted in

Table 4. Regression coefficients and standard errors of the multiple regression models of the equivalent weighted accelerations in the vertical axis on the seat and on the floor of the fork-lift trucks, as a function of the individual factors and their interactions

	a_{Zw} seat		a_{Zw} floor	
Independent variables	Coefficient	SD	Coefficient	SD
Constant	0.313	0.134	−0.231	0.140
Track	0.938	0.036	1.356	0.038
Load	—	—	−0.225	0.035
Truck	−0.164	0.048	—	—
Tyre	—	—	—	—
Seat	−0.868	0.045		
Weight	−0.136	0.020	—	—
Speed	0.095	0.010	0.129	0.010
Track–truck	—	—	−0.272	0.045
Track–tyre	—	—	−0.369	0.050
Seat–truck	0.449	0.054	—	—
Seat–tyre	0.387	0.068	—	—
R^2	0.712		0.772	

Table 5. Correlation and regression coefficients (and standard errors) for the simplified multiple regression models of the equivalent weighted acceleration in the vertical axis on the seat and on the floor as a function of the individual factors (without interactions)

	a_{Zw} seat		a_{Zw} floor	
Independent variables	Coefficient	SD	Coefficient	SD
Constant	0.271	0.134	−0.124	0.154
Track	0.929	0.037	1.156	0.034
Load	—	—	−0.225	0.036
Truck	—	—	−0.144	0.034
Tyre	0.274	0.040	−0.202	0.037
Seat	−0.601	0.035		
Weight	−0.138	0.022	—	—
Speed	0.088	0.010	0.129	0.011
R^2	0.682		0.750	

the ANOVA analysis, there is a significant interaction effect between the diagonal tyres (tyre = 1) and the anti-vibration seat (seat = 1). The only other significant interaction is for the suspended seat used on electric trucks. These interactions, although very significant, do not considerably increase the validity of the mathematical prediction model ($R = 0.844$ against 0.826 without them), so that the simplified model can be used. This shows the importance of the roughness of the track ($+0.93$ m s^{-2} on a paved track) and the significant reduction given by a suspended seat (-0.60 m s^{-2}). The fact of being loaded or not, as well as the type of truck (diesel or electric) apparently play a role only through the driving speed, different in each case.

The same conclusions hold concerning the acceleration on the floor of the truck: two interactions are playing a significant role but do not raise considerably the validity of the model (from $R = 0.866$ to 0.879). The simplified model for the acceleration on the floor shows about the same track effect than for the acceleration on the seat ($+1.16$ m s^{-2}) while there are light effects of the load (-0.22 m s^{-2}) and the type of truck (-0.14 m s^{-2}) besides the effect on the driving speed. There is obviously no effect of the seat while the effect of the worker's weight is not significant.

These models can be used to predict the vertical acceleration in a given working situation. For example, in the case of an electric fork-lift truck equipped with a suspended seat and cushion tyres and working on a medium smooth ground (track = 0.5), the equivalent weighted acceleration in the Z axis on the seat, for an average worker driving at about 10 km h^{-1} would be about 1 m s^{-2}. According to the health criterion described in ISO 2631, this level of exposure could be tolerated for about 3 h.

DISCUSSION

The validity of the results presented in this paper is a priori restricted to the conditions of the study: fork-lift trucks from one maker only, ranging from 1.5 to 4 tons in nominal load. Two seats were compared that might not be representative of all the seats that can be used on such trucks. In addition, the choice of tyres was limited in size and in brand. Comparisons must therefore be made with data from other sources, before the results can be used to assess the exposure in any situation in industry.

Few data are reported in the literature. Griffin (1990) gives one example for which the weighted a_{Zw} can be estimated at about 1.6 m s^{-2} while Dupuis and Zerlett (1986) mention a range of magnitude of 0.4–2.0 m s^{-2}. More results are presented by Donati *et al.* (1993) in a study on the effects of tyres on vibration in two 1.5-ton fork-lift trucks. The tests were made however on a running track with artificial obstacles whose representativity was not discussed. Statistical analysis of the data presented in that report confirms that accelerations are largely predominant in the vertical axis. The order of magnitude is about 1 m s^{-2} for an electric truck equipped with cushion tyres and unloaded. This is not inconsistent with our results as the characteristics of the seat and the track are not known.

In another study, Boulanger and Galmiche (1992) reported a_{Zw} amplitudes of the order of 1.13 and 1.97 m s^{-2} for two trucks, respectively, of 2.5 and 1.5 tons, without load. Reasons for this discrepancy were not discussed. Our results suggest on the contrary that vibration amplitudes do not vary significantly with the size of the truck, in the range investigated (1.5–4 tons). The different studies agree concerning the reduction of vibration associated with the carrying of a load: the order of magnitude varies however from -0.02 m s^{-2} in the Donati *et al.* (1993) study to -0.3 m s^{-2} for Boulanger and Galmiche (1992). Our results suggest that this effect might rather be associated with the reduction of the driving speed of the fork-lift truck. According to Table 3, this reduction is of the order of magnitude of 1.7 km h^{-1} and the mean acceleration reduction would be 0.15 m s^{-2}.

The role played by the tyres is more debatable. Boulanger and Galmiche (1992) reported differences up to 0.54 m s^{-2} with two different sets of cushion tyres, the hardest ones giving the highest values. This however was the result of a single measurement which, according to the authors themselves, could be related to variations in driving conditions.

Comparing cushion and inflated tyres, Donati *et al.* (1993) reported a slight reduction (average: 0.12 m s^{-2}) with the latter, while our study leads to an increase by 0.24 m s^{-2}. This is actually related to the cut-off frequency of the seat. Both studies report a lowering of the predominant one-third octave band from 5 Hz with cushion tyres to 4 Hz with inflated tyres, as shown by Fig. 3. The cut-off frequencies of the Donati study were, however, lower than in our study, so that their suspended seat attenuated while the EBLO seat amplified the vibration. As concluded by Donati *et al.* (1993), "a vehicle with pneumatic tyres must be fitted with a seat which has a lower cut-off frequency that if the vehicle was fitted with stiffer tyres".

The effect of the driving speed needs some further analysis. The regression of the speed on the main factors gives the following expression:

$$\text{speed} = 13.66 - 1.18 \times \text{track} - 1.60 \times \text{load} - 0.86 \times \text{truck} - 0.36 \times \text{tyre}$$

with a correlation coefficient of 0.600.

This must be taken into account when using the results presented in Table 5 for the prediction of the exposure level. This is particularly significant concerning the increase in vibration when driving on a very rough track.

CONCLUSIONS

The present study made it possible to analyse in details the vibration exposure of fork-lift truck drivers. The main conclusions are:

—on all trucks, vibration is dominant in the vertical axis and the average weighted acceleration on the seat, averaged over all investigated conditions, is 1.59 m s^{-2};

—the dominant one-third octave bands are centred between 3 and 6 Hz. They are lower, on average, by one-third octave for trucks fitted with inflated tyres, compared to cushion tyres;

—the accelerations are systematically lower when the truck is loaded, mainly due to the associated reduction of the driving speed;

—electric trucks vibrate slightly less than the diesel trucks, again mainly due to the reduction of the driving speed;

—the roughness of the driving track influences considerably the vibration level: when driving on a rough paved track the acceleration is about 70% greater than when the track is smooth;

—the vibration on the floor of the truck is smaller by about 0.2 m s^{-2} with inflated rather than cushion tyres. On the seat, on the other hand, it can be greater or smaller depending upon the cut-off frequency of the seat (being above or below 4 Hz). In the case of a 'normal' seat, such as the low-cost seat equipping standard trucks, cushion tyres are probably more advisable. Inflated tyres are preferable when and only when a special low cut-off frequency seat is used.

Based on these results the main technical actions capable of reducing the vibration amplitudes to which the workers are exposed are:

(1) the levelling of the track;
(2) the use of a suspended seat, preferably with a cut-off frequency lower than 4 Hz;
(3) if the previous point is fulfilled, the choice of inflated tyres;
(4) in any case, the adjustment of the driving speed as a function of the driving conditions (track, load, truck, etc.).

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