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A PROCEDURE FOR DEVELOPING A VIBRATION TEST METHOD FOR SPECIFIC CATEGORIES OF INDUSTRIAL TRUCKS

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Industrial trucks drivers may be exposed to high values of whole-body vibration with frequencies below 10 Hz due to surface irregularities and the lack of suspension systems on these vehicles. Machinery Directive 89/392/EEC and its amendments require that vibration measurements be made and values put into the instruction books if the whole body vibration values are greater than $0{\cdot}5\ \mathrm{m/s^2}$. A standard (pr EN 13059) has been prepared to provide a method so that different establishments obtain comparable and representative results of vibration measurements. The procedure consists of measuring the vibration transmitted to the operator when the truck is travelling over a test track made up of a straight length of good quality surface with obstacles whose characteristics depend on the type of truck and its wheel characteristics. The aim of this paper is to report the methodology which was used to develop the test method for each specific category of industrial truck. This paper emphasizes the qualities to be expected from a vibration test code which should provide repeatable, representative, valid, and inexpensive results.

1. INTRODUCTION

Industrial truck drivers may be exposed to high values of whole-body vibration with frequencies below 10 Hz due to surface irregularities and the lack of suspension system on these vehicles [1–4]. It has been found through epidemiological studies that exposure to whole-body vibration combined with poor posture indeed increases the risk of lower back disorders [5, 6]. In 1996, Machinery Directive 89/392/EEC and its amendments [7] came into force. Under this directive, mobile machinery manufacturers (including industrial truck manufacturers) are required to improve the safety of their products by reducing the emission values of physical agents (namely noise and vibration) to the lowest possible level by taking into account all available technical progress, if possible, at the design stage, and to give information on the vibration emission transmitted to the whole body of operators if the weighted r.m.s. (root mean square) acceleration measured under the feet or under the buttocks exceeds $0{\cdot}5\ \mathrm{m/s^2}$.

European standards have to determine how these requirements can be fulfilled. Thus a standard (pr EN 13059) has been prepared by CEN/TC150/WG8 to provide a type test which will enable the vibration emission of different industrial trucks of the same family to be compared [8]. Type tests require accurate and repeatable measurements because it is essential that different establishments obtain comparable results. Three different basic methods were considered to test the machines.

(a) The first is to measure the trucks under real conditions. This method is inexpensive and easy to carry out, but it is difficult to control the repeatability of results from one location to another. Previous measurements showed variations in weighted root mean

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square acceleration ($a_{w,rms}$) of between 0·5 and 2 m/s^2 for the same truck depending on the ground surface and truck speed [1].

(b) The second method consists of measuring the vibration transmitted to the operator when the truck is travelling over an artificial test track made up of a straight length with obstacles. The Agriculture Tractor Seat Directive 78/764/EEC and its amendments have recommended as such a procedure since 1978 to assess seat efficiency at reducing vibration [9]. In 1988 Probst *et al*. used an artificial track with twelve obstacles to compare vibration values emitted by different counterbalance trucks [10]. The method was adopted by Boulanger *et al*., to compare truck seats [11]. The track proved too severe with the machines tested compared to the vibration values obtained under real conditions. Furthermore, the repeatability was poor.

(c) Tests in the laboratory on a vibration simulator may solve the problem of lack of repeatability raised in (b) and (c), but this third method would be too expensive for most manufacturers.

Method (b) was therefore selected by the members of the CEN working group in charge of developing the new standard, with a view to improving it to obtaining repeatable and inexpensive results. It is also important that the method reproduces vibration values typical of the machinery in normal use, although values obtained from these tests should not be assumed to indicate with any precision the vibration magnitude expected at work. The method is based on only one truck operating mode, namely travelling, because only this mode may expose the driver to significant whole body vibration. In practice, exposure over a working day is a mixture of travelling, lifting and engine idling, and the average vibration exposure values will differ from one site to another.

This paper reports the procedure used to develop the test method for each specific category of industrial trucks and the experiments carried out to optimize it. This type text is used to emphasise the qualities which should be expected from a draft vibration type testing standard before submitting it for the approval of member countries.

2. PROCEDURE FOR DEVELOPING THE TEST METHOD

The type test must be applicable to industrial trucks as different as pallet trucks or container trucks, with appropriate adaptation of some test parameters. The following procedure was followed to develop appropriate tests for each specific category of trucks.

(a) Information was collected on vibration values at the seat base and on the seat pan, measured under real conditions when the trucks were mainly travelling. The real vehicle speeds and ground surface characteristics (obstacles such as door sills, manhole covers, ramps, fractures, etc.,) were assessed.

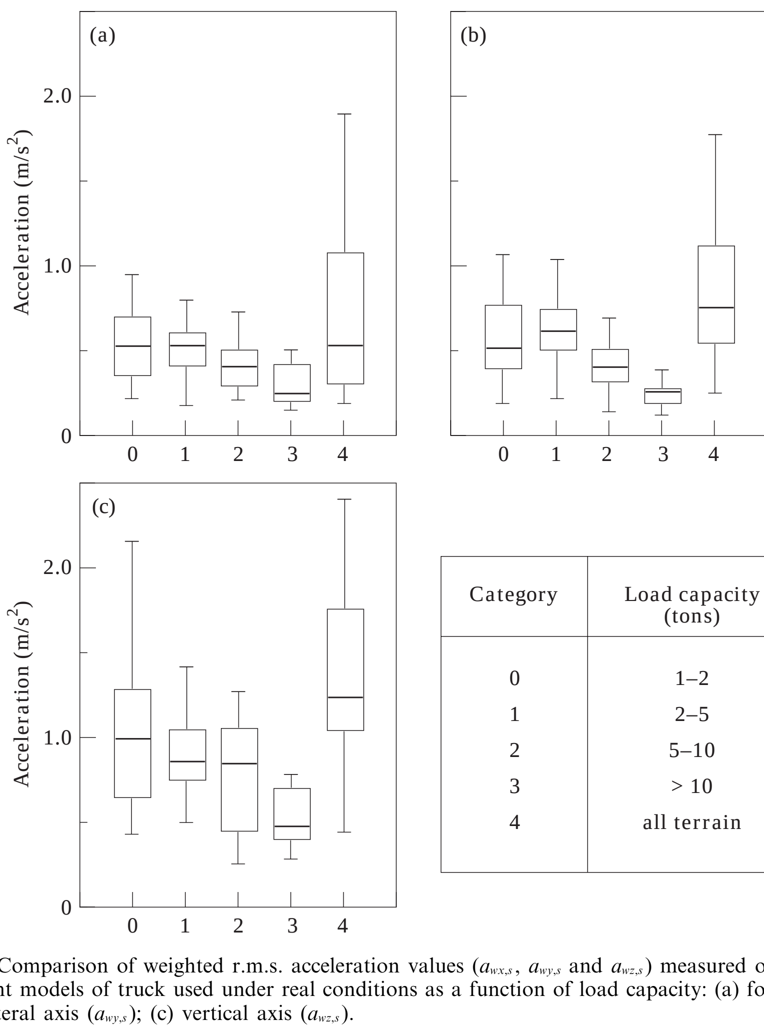
(b) Target acceleration values at the seat base were selected which correspond to the mean acceleration values measured in (a) on many trucks of a specific category. The speeds adopted were sufficiently low for the majority of trucks of each specific category (it should be possible to drive the trucks over the test track without difficulty), but sufficiently high to be realistic of use in the field.

(c) The test track characteristics were adjusted so that the vibration values under the seat are roughly equal to the target acceleration selected in (b). The test track should be as short as possible, but long enough to allow vibration analysis and acceptable repeatability of results.

(d) The repeatability of measurements was checked, and causes of variability (speed, tyre pressure, smoothness of the test track surface, etc.,) were studied. Comparison tests were organised.

3. VIBRATION VALUES MEASURED UNDER REAL CONDITIONS

More than 100 different industrial trucks were tested under normal conditions of use [1, 12]. When it was not possible to take part directly in the production cycle, measurements were carried out within the factory walls over a floor area similar to the one usually covered by the vehicles. Loads to be handled came from workshops where the trucks usually took on supplies. Vibration measurements were carried out by application of ISO 2631 [13] on the seat pan, using a semi rigid interface containing three linear accelerometers placed below the driver's bottom and at the seat base, and by means of three linear accelerometers fixed by a magnet on a rigid part of truck floor. The sensitive axis of each linear accelerometer was positioned along the following orthogonal axes parallel to the driver whole body co-ordinate system: fore and aft (x), lateral (y) and vertical (z). Figure 1 compares for different categories of trucks the weighted r.m.s. acceleration values obtained on the seat as a function of load capacity. The main axis is generally the vertical axis. The highest vibration levels were found for trucks with a load capacity of less than 2 tons and with small wheels when in use on poor surfaces, and for all-terrain trucks.



Category	Load capacity (tons)
0	1–2
1	2–5
2	5–10
3	> 10
4	all terrain

Figure 1. Comparison of weighted r.m.s. acceleration values ($a_{wx,s}$, $a_{wy,s}$ and $a_{wz,s}$) measured on the seat pan of 77 different models of truck used under real conditions as a function of load capacity: (a) fore and aft axis ($a_{wx,s}$); (b) lateral axis ($a_{wy,s}$); (c) vertical axis ($a_{wz,s}$).

TABLE 1

Definition of the seven categories of industrial trucks

Category	1	2	3	4	5	6	7
Wheel Mean diameter ($\varnothing$) in mm	$\varnothing \leqslant 200$	$\varnothing \leqslant 450$	$\varnothing \leqslant 645$	$645 < \varnothing \leqslant 900$	$900 < \varnothing \leqslant 1200$	$1200 < \varnothing \leqslant 2000$	$700 < \varnothing \leqslant 1200$
Typical family of tyres	High load non-rubber solid tyres	High load non-rubber solid tyres or cylindrical/ conical base rubber solid tyres	Rubber solid tyres or pneumatic tyres	Rubber solid tyres or pneumatic tyres	Pneumatic	Pneumatic	Pneumatic
Load capacity (kg)	$\leqslant 3000$	All capacities	$\leqslant 3500$	$3500 <$ L.C. < 8000	$8000 <$ L.C. < 18000	L.C. > 18000	All
Family of trucks	Platform trucks, trucks rider controlled,	Reach trucks, articulated trucks, etc.	Straddle trucks, counterbalance trucks below 8 tonnes, etc.		Trucks above 8 tonnes		All-terrain trucks
Target acceleration at seat base (m/s²)	0·8	0·8	1·5	1·4	1·3	0·4	1·25

According to manufacturers, the speed generally ranges from 5 to 10 km/h for trucks on high-load solid tyres, and from 5 to 18 km/h for the others. Ground surface irregularities of a few mm are normal for trucks on high load solid tyres or bandages, and a few cm are acceptable for trucks on solid cushion or pneumatic tyres.

Using these results, the standard pr EN 13059 divides industrial trucks into seven categories based on wheel diameters (load capacity and wheel diameter are related for the main truck families) and type of tyres, as shown in Table 1. All-terrain trucks form a separate category as they are the only ones designed to travel on rough ground.

TABLE 2

Effect of main parameters on the weighted r.m.s. acceleration ($a_{wz,B}$) measured at the seat base on a 1·5 tons counterbalance truck

	Parameter	Effect on $a_{wz,B}$ (%)
Obstacle	height: 0·5–1 cm	↑ 50
	1 or 2 obstacles	↑ 50
	width 10–20 cm	↑ 20
	slope	no effect
Artificial track smoothness	loose chipping	↑ 30–50
Truck	speed 7–14 km/h	↑ 100
	0–60% nominal load	↓ 10–40
	solid to pneumatic tyres	↓ 5–15

↑ = increase; ↓ = decrease.

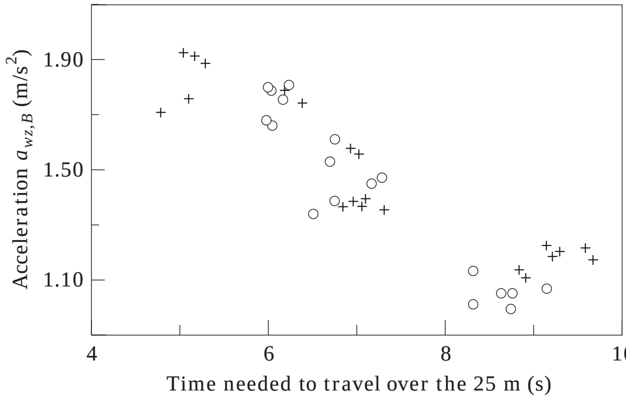


Figure 2. Effect of speed and driver on the vertical weighted r.m.s. acceleration measured at the seat base of a 1·5 tons counterbalance travelling on the test track with 0·5 cm high obstacles. Key: ○, operator 1; +, operator 2.

ADJUSTMENT OF TYPE TEST PARAMETERS

4.1. DESCRIPTION OF TYPE TEST

Systematic testing with two counterbalance trucks allowed the main parameters likely to affect vibration values to be identified. These are the following: for the track, the number and dimensions (height, width, slope) of obstacles, the quality and length of track surface; for the truck, the speed, the load, and the tyres. In addition, the seat and its adjustments when measurements are made on the seat pan instead of at the seat base; for the operator, driving attitude and weight.

The main results of these systematic tests are summarized in Table 2. Figure 2 shows a linear relationship between the vehicle speed and weighted vertical vibration for a 1·5 tons counterbalance truck. Similar relationships were found by manufactureres for other categories of trucks. Two operators participated in the test with the 1·5 tons counterbalance truck. No significant differences were observed for vibration values obtained at the seat base.

Specific tests were then made by INRS on eleven industrial trucks belonging to five different categories (see Table 3), for different conditions, to adjust the test conditions [14–16]. Complementary experiments were also carried out by the Health and Safety Executive for other categories [17–19].

TABLE 3

Industrial trucks studied to adjust the test conditions

Category [8]	Number of vehicles measured	Load capacity (tons)	Wheel diameter (cm)	Tyres
Pallet truck (I)	2	1·5–2	8–24	High load solid
Reach truck (II)	1	1·6	28–30	High load solid
Counterbalance truck (III & IV)	2	1·5–1·6	44–55	Cushion solid
	2	2·5–5	64–85	Pneumatic
All-terrain truck (VII)	4	2·8	100–120	Pneumatic

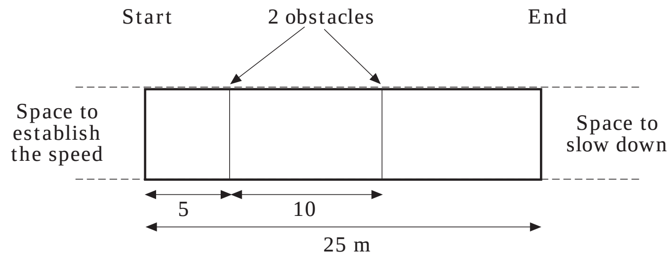


Figure 3. Characteristics of the recommended test track.

These different experiments enabled the type test as described below, to be defined as follows. For all categories, the recommended test track (see Figure 3 and Table 4) consists of a straight surface, 25 m long (category one is only 15 m), with two obstacles with heights ranging from 0·5 (category one) to 3 cm (category seven). Trucks run forwards at a constant speed with a load of 60% (except category 6 which are tested unloaded) of the rated load capacity (see Table 4). The smoothness of the surface is defined by the ratio of the r.m.s. value of the weighted acceleration measured on the truck travelling on the test track without the obstacles and the corresponding value obtained with the obstacles; this ratio should be below 50% to ensure reproducible results between different measuring sites. Each model of truck should be measured, and the measurements should be repeated for each option of equipment which may affect the results. A series of tests must be carried out each time consisting of N consecutive runs on the test track. Measurements are continued until a valid test series has been obtained: i.e., until the coefficient of variation (ratio between the r.m.s. acceleration standard deviation and the corresponding mean values) is less than 0·15. Generally, the test is valid after five to eight runs.

4.2. ACCEPTABILITY OF VIBRATION MEASUREMENT AT THE SEAT BASIS

The vibration value declared is the vibration measured on the truck seat. If the Seat Effective Amplitude Transmissibility (S.E.A.T.) measured in laboratory [20] is known, the vibration can also be measured at the seat base, and the seat vibration deduced by calculation. The results measured at the seat base have a better repeatability than those on the seat pan because they do not depend on driver dynamic characteristics—especially his weight—and seat adjustments (measurements on the seat pan must be made with two

TABLE 4

Conditions of the test according to the category[8]

Category (see Table 1)	1	2	3	4	5	6
Length of test track (m)	15	25	25	25	25	25
Height of obstacle (mm)	5	5	8	10	10	15
Upper width of obstacles (cm)	15	15	15	15	15	15
Slope of obstacles (°)	90	90	90	90	90	90
Number of obstacles	2	2	2	2	2	2
Distribution of obstacles (m)	4 and 6	5 and 10	5 and 10	5 and 10	5 and 10	5 and 10
Speed (km/h)	5	7	10	10	10	10

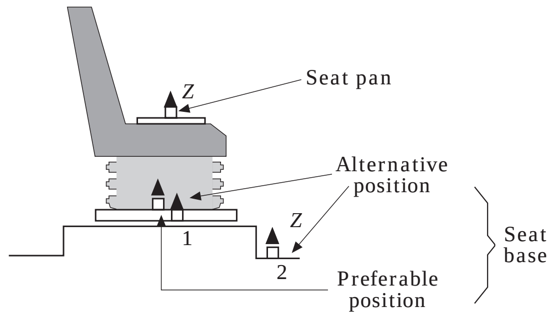


Figure 4. Preferred and alternative positions of accelerometers on the seat pan and at the seat base.

different operators weighting 55 and 98 kg as recommended by standards on seats [20, 21], and repeated for each model of seats which can be fitted to the truck).

4.2.1. *Effect of location of accelerometers*

Unfortunately, quite often it is not possible to mount the accelerometer at the centre of the seat mounting and alternative positions around the seat are used. Two experiments were carried out to study the effect of accelerometer location on vibration magnitude:

Firstly, a 1·5 t counterbalance fork lift truck was equipped with six vertical accelerometers, one located at the seat mounting centre, four around the seat in the same horizontal plane (front, rear, left and right) and one on the floor, 30 cm below. The unloaded truck was tested on the artificial track in accordance with the instructions of the draft standard on trucks, but with either the four wheels or only the right wheels travelling over the two obstacles.

Secondly, the acceleration magnitudes at all points around the seat mounting centre were calculated using a numerical model of the 1·5 t counterbalance fork lift truck developed with a software called ADAMS (this is a software designed to study the dynamic behaviour of multibody structures). The calculation was made with the model running over a 0·8 cm high obstacle at 10 km/h.

Under test conditions, the effect of the location of the verticle accelerometer mounted on the side of the truck within 50 cm of the seat mounting centre, on the r.m.s. acceleration values of the frequency weighted vibration was less than 10%. On the other hand when the accelerometer was fixed on the rear of the seat the maximum difference was of about

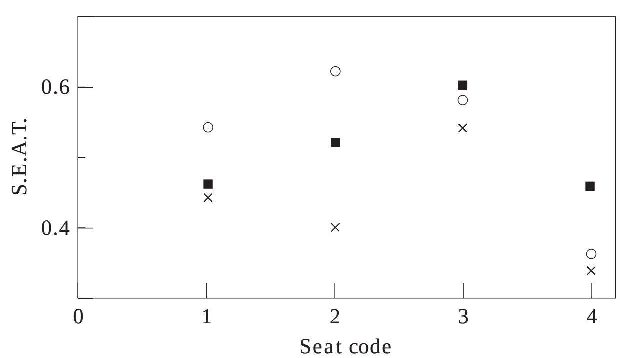


Figure 5. Comparison between the average S.E.A.T. values of the seats tested on the truck travelling over the artificial test track (loaded and unloaded) and in the laboratory (class I). Key: ○, loaded (truck; ■, laboratory; ×, unloaded truck.

TABLE 5

Comparison between the weighted r.m.s. acceleration values on the seat pan obtained by direct measurements or deduced by calculation from the S.E.A.T. values measured in the laboratory

		Weighted r.m.s. vertical acceleration (m/s^2)		
		Direct measurements on loaded truck		
Seat code		Seat base ($a_{wz,B}$)	Seat pan ($a_{wz,S}$)	Calculation $a_{\omega z,B}$ × S.E.A.T.
1	range	1·35–1·59	0·78–0·86	1·49 × 0·46 = 0·69
	mean	1·49	0·81	
2	range	1·41–1·55	0·89–1·04	1·48 × 0·52 = 0·77
	mean	1·48	0·96	
3	range	1·41–1·51	0·78–0·90	1·44 × 0·60 = 0·86
	mean	1·44	0·85	
4	range	1·43–1·77	0·58–0·62	1·60 × 0·36 = 0·58
	mean	1·60	0·60	

20%. This may be explained by the truck pitching mode which is excited by the obstacle. Therefore the standard pr EN 13059 recommends that the alternative positions of accelerometers will be at the same level as the seat base but on the side of the truck perpendicular to the direction of travel (see Figure 4).

4.2.2. *Comparison between seat performance in the laboratory and field*

To compare seat performance in the laboratory with that in the field when the truck is travelling over the artificial test track defined above, the vibration isolation efficiencies of four suspension seats were measured under both conditions. The seats were successively fitted to a vibration simulator and a counter balance truck with a load capacity of 1·5 t. The isolation efficiencies of the seats were evaluated by the vertical vibration transmission ratio (S.E.A.T.), which is the ratio of the frequency weighted root mean square acceleration on the surface of a seat to that at the seat base.

The measurements were made in the laboratory according to the draft standard prepared by CEN/TC231/WG9 to test the seats of industrial trucks [20]. The input vibration corresponded to class I which is given by this standard to represent categories 1, 2 and 3 of trucks (trucks with wheel mean diameter lower than 645 mm). The four suspension seats were tested with only one person (weight = 75 kg) who was also the truck driver during the measurements on the artificial track.

The distribution of mean S.E.A.T. values obtained for each seat in the laboratory and in the field is given in Figure 5. The four seats were efficient at attenuating the truck vibration with a S.E.A.T. ranging from 0·3 to 0·6. The results show a better performance

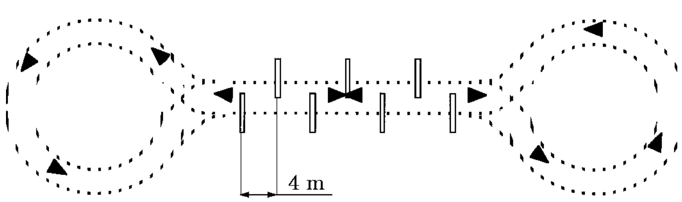


Figure 6. Alternative test track with seven one-side obstacles.

TABLE 6

Comparison between natural and artificial conditions of the weighted r.m.s. vertical acceleration ($a_{wz,B}$) measured at the seat base on three all-terrain trucks

Track		$a_{wz,B}$ (m/s^2) Truck A	B	C
Natural		1·2–1·3	1·2–1·5	1·5–1·6
CEN draft standard [8]		1·5–1·6	1·6–1·7	1·7–1·8
US proposal	5 km/h (7 cm)	0·9–1·0	1·3	1·5
	7 km/h (5 cm)	1·3–1·4	1·2	1·8

of the four seats when the truck was unloaded due to higher frequency content and greater intensity of the floor input vibration. The difference depends on the seat (between 10 and 40%). In all cases, the S.E.A.T. differences between the laboratory and field (with the truck loaded as recommended by the draft standard) are lower than 25%. For two seats the performance was better in the field, and for the two others it was less good. Table 5 shows that the weighted r.m.s. vertical acceleration values on the seat pan deduced by calculation from the laboratory S.E.A.T. values are consistent (maximum difference lower than 25%) with those obtained by direct measurements.

This relatively small difference (S.E.A.T. varies greatly with the vibration input magnitude as seen in previous experiments) is due to the fact that seat input vibration was similar for both the laboratory and field tests. Indeed, the artificial test track was adjusted so that the floor vibration measured on the trucks was, on average, representative of the vibration measured under real conditions in factories. A similar policy was followed when developing the laboratory seat test code.

5. REPEATABILITY OF MEASUREMENTS

5.1. GENERAL CASE

Once all of the parameters had been properly set, good repeatability was obtained for one truck during consecutive tests made on the same day when applying the proposed standard. Whatever the category of truck tested, there was no difficulty in respecting the value of the coefficient of variation, set to 0·15. It was also verified that the same results were obtained for a 1·5 tons counterbalance truck equipped with solid tyres and tested on the same test track at different times of the year. Simultaneous measurements made by INRS and one manufacturer on three different industrial trucks gave similar results. Vibration measurements in accordance with the draft standard were carried out by at least seven truck manufacturers and four independent laboratories on different vehicles. No inconsistent vibration value was found between the different measuring sites on similar trucks except for all-terrain trucks.

5.2. CASE OF ALL TERRAIN TRUCKS

These latter trucks are very different from others because they are generally equipped with large pneumatic tyres. When the test was repeated at different times of the year in varying temperature conditions, vibration value differences of up to 40% were found for one vehicle, primarily explained by variation of tyre pressure. The difference was 10% for the two other vehicles. There was concern that the artificial test code does not adequately represent the working environment.

An additional experiment was carried out with three all-terrain trucks to check the repeatability of the results obtained at different periods of year, and to compare the ranking of vibration values obtained under natural or artificial conditions. The three vehicles with a load of 60% of the rated load capacity were measured under the following four different conditions: (i) natural track; each truck ran forwards at a constant speed of 10 km/h along a circular 500 m rough path of dry earth; (ii) artificial test track in accordance with the method described in section 4.1; the straight surface was barred by two obstacles 3 cm high; (iii, iv) artificial test track which consists of a flat surface with seven obstacles on the left or right sides and a distance between obstacles of 4 m (see Figure 6); two different conditions were tested: obstacle heights of 5 cm and a speed of 7 km/h, and obstacle heights of 7 cm and a speed of 5 km/h; each truck was run for three min on each set-up, Table 6 shows that the rankings of vibration values were similar for natural and artificial conditions except in one case.

6. CONCLUSIONS

The standard pr EN 13059 on the measurement of industrial truck emission vibration is based on four requirements which should be expected of all type testing standards: repeatability—this was achieved by artificially eliminating the main sources of variability that occur under real conditions; representativity—the test conditions were adjusted so that the vibration values obtained are, on average, similar to those measured in the field; validity—it was checked that if a truck transmits on average significantly higher vibration than another under real conditions, this is still valid within the test code; low cost.

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