Noise and Vibration

Studies and Research Projects

REPORT **R-709**

Evaluation of Whole-Body Vibration Exposure of Operators of Soil Compactors

Subhash Rakheja
Ario Kordestani
Pierre Marcotte

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Evaluation of Whole-Body Vibration Exposure of Operators of Soil Compactors

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EXECUTIVE SUMMARY

Single-drum vibratory compactors are widely used for compaction of soils and road building. Such compactors are basically articulated vehicles comprising a vibratory drum (roller) as the front unit and a single-axle tractor as the rear unit. The drum integrates an eccentric rotating mass to achieve efficient soil compaction through vibration of the eccentric mass. The dynamic interactions of the drum and the tires with the terrain, coupled with dynamics of the articulated vehicle with asymmetric load distribution, yield comprehensive magnitudes of whole-body vibration (WBV) to the seated operator through the seat, which in most vehicles used in Québec is limited to a polyurethane foam cushion. This study investigates vibration properties and operator exposure to WBV of single-drum vibratory soil compactors through measurements, and presents spectral classes of vibration that could be applied for identifying desired interventions. Two test series were undertaken to characterize the mechanical vibration properties of the vehicles and vibration exposure of the operators. The first test series was performed on a test-track under controlled conditions, namely, the speed, the amplitude of vibration due to the rotating mass integrated within the drum and the soil properties. The objective was to determine the vibration behaviours of the vehicles in terms of dominant ride frequencies and probable vibration modes. The second test series was undertaken at two different worksites in Québec in order to quantify and assess the WBV exposure under typical working conditions.

The field test series was designed to measure vibration transmission properties of the vehicles at the worksites in two distinct operating modes: compaction and transit. The variations in soil density and vibrator amplitude in the compaction mode were also considered to study the ranges of transmitted vibration. Each test series involved two different vehicles representing the greatest population of vehicles used in Québec. The controlled conditions test series employed two brand-new 10-ton compactors (a 4-cylinder and a 6-cylinder machine), compaction of low-density and high-density soils with ‘low’ and ‘high’ settings of the vibrator amplitude, and transit at a nearly constant speed of 10 km/h. The worksite test series employed: (i) a 7-year-old 10-ton compactor, introduced by operators as the “average” vehicle from the WBV standpoint; and (ii) a 2-year-old 13-ton compactor, introduced as one of few equipments representing improved vibration performance, while the operating conditions were entirely selected by the operators.

The vehicles in the controlled test series were instrumented to measure vibration responses for characterizing their vibration properties. The measurements of vehicles at the worksites were limited to translational and rotational vibrations of the cabin and operator seat for characterization and assessment of the exposure. The field tests also involved repeated compaction and transit runs. The first series involved 27 and 23 runs, respectively, for the 4- and 6-cylinder vehicles, while the second series comprised 19 and 15 runs for the 10- and 13-ton vehicles, respectively. The results obtained for comparable runs revealed reasonably good repeatability, and were thus combined to define the ranges of vibration spectra along the longitudinal (x), lateral (y), vertical (z), pitch (θ) and roll (φ) axes.

The measurements revealed that the vibration behaviour of such vehicles is strongly dependent upon the mode of operation. In the compaction mode, the vehicles invariably operate at very low speeds, in the order of 3 km/h, and the vibration behaviour is mostly determined by dynamic properties of the soil and the centrifugal force due to rotating eccentric mass (referred to as the amplitude of the vibrator), particularly its angular speed (near 30 Hz). Compaction of high-density surfaces often causes hopping motion of the drum (loss of contact with the terrain surface), which resulted in dominant vibration at one-half the angular frequency (15 Hz). The magnitude of low frequency vibration was generally small in this mode of operation.

The magnitude of low frequency vibration, however, increased considerably in the transit mode along all the axes due to dynamic interactions of the drum and tires with the uneven terrain, and

higher speeds (near 10 km/h). The measured data acquired during the worksite runs were used to characterize the vibration transmitted to the cabin and the seat. Attempts were made to group the compaction runs data corresponding to two different vibrator amplitudes, 'low' and 'high'. This could, however, be achieved only for the 10-ton vehicle, since the operator of the 13-ton vehicle opted to perform all the runs with only the 'low' amplitude setting. The variations in the vibrator amplitude revealed notable effects on the low frequency vibration (<10 Hz), while the effect on high frequency vibration (>10 Hz) was most significant, particularly at 15 Hz. The dominant ride frequencies of the two vehicles were quite comparable to those observed from the data acquired at the test track during high-density soil compaction, although the magnitude of vibration of the 10-ton machine was considerably higher. The vibration magnitude of the 13-ton machine, however, was considerably lower, in-part due to the 'low' amplitude compaction.

The magnitude of low frequency vibration at the worksites was generally lower than that measured on the test track for the 10-ton machine. This was mostly attributable to relatively lower transit speed at the worksites than the speed used on the test track (near 10 km/h). The vibration spectra of the 13-ton machine generally revealed amplification of vibration by the cabin mounts and the seat. The data were used to determine the ranges of vibration, which could be applied to define spectral classes of vibration and to explore better designs of the cabin mounts, the drum mounts and the suspension seat to reduce transmission of low frequency vibration. These spectra would also be applicable for simulation-based design approach in verifying the dynamic of vehicle models.

The measured data were subsequently analyzed to assess WBV exposure using ISO-2631-1 and EC (European Community, EN 2002/44/EC) guidelines. The 10-ton unit revealed considerably higher exposure values in compaction compared to the 13-ton machine, which was most likely due to the 'low' amplitude compaction by the latter machine. In the transit mode of operation, the 13-ton machine revealed considerably higher values of frequency-weighted cabin vibration, which was partly attributed to its higher roll and pitch vibration compared to the 10-ton machine. The cushion seat of the 10-ton machine, however, caused nearly 60% amplification of the cabin vibration. This amplification was only 16% for the suspension seat employed in the 13-ton machine. The daily exposure values, A(8), for the two machines were computed considering three different exposure patterns of compaction and transit durations: 6, 6.25 and 6.5 hours of compaction and 1, 0.25 and 0.5 hours of transit, respectively, together with 1 hour of other activities in a vibration-free environment. The mean A(8) values based on the seat vibration of the 10-ton machine exceeded the daily exposure action value of 0.5 m/s^2 recommended in the EC directive, for all the three exposure patterns considered. The exposure values corresponding to the cabin vibration were only slightly above the action value for all three patterns. The mean daily exposure values for the 13-ton machine based on the cabin vibration were considerably lower than the action value, while those based on the seat vibration approached 0.47 m/s^2. The exposure values derived for this machine, however, would be applicable only for 'low' amplitude setting of the vibrator. The compaction with 'high' amplitude setting may yield higher exposure values.

These results suggest that the use of an adequately tuned suspension seat would be vital for limiting the exposure below the action value, particularly for the 10-ton machine, which is most representative of the compactors used in Québec. It was observed that most of the compactors used in Québec do not employ a suspension at the seat and the cabin suspension is limited only to rubber mounts. Further efforts are also recommended to examine the design of suspension seats used in the newer vehicles and their actual adjustment in the field to limit the transmitted vibration. Further efforts in identifying optimal cabin mounts are also desirable and recommended for limiting the WBV exposure.

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1. INTRODUCTION

Vibratory soil compactors are articulated vehicles designed to achieve efficient compaction of the soil and road base-layers through a vibratory drum/roller integrating an unbalanced rotating mass. The vehicle is supported on large size tires at one of its axles and a vibrating drum on the other axle, as seen in Figure 1.1. This asymmetry yields considerable longitudinal and pitch motions of the vehicle frame (body) and the cabin (operator station), in addition to the vertical motions arising from interactions of the wheels and the vibratory drum with the terrain. The cabin and the drum are supported on elastic mounts, which help suppress only high frequency vibration. The low frequency whole-body vibration (WBV) arising from the drum/terrain and wheel/terrain interactions and dynamics of the asymmetrically loaded vehicle are directly transmitted to the operator through the driver seat, which in the vast majority of the vehicles employed in Québec is limited to a polyurethane foam cushion. The vibration environment of such vehicles could thus be characterized by that of the resonance of a lightly damped system formed by the unsuspended vehicle and the tires on only one of the axles. The prolonged occupational exposure to such low frequency whole-body vibration has been associated with increased risk of disorders in the lumbar spine and the connected nervous system (e.g., Bovenzi and Hulshof, 1998; Bovenzi et al., 2006; Bongers et al., 1988; Bernard, 1997).

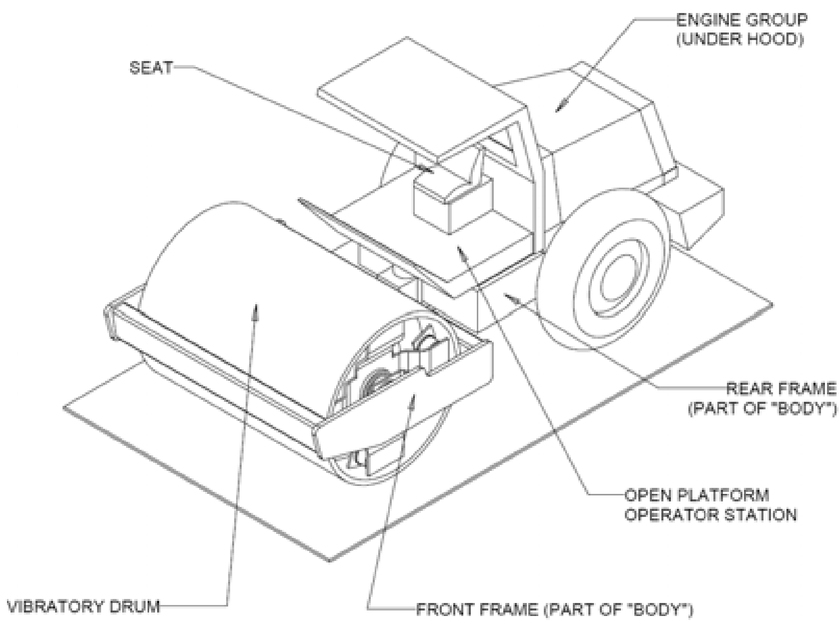


Figure 1.1: Schematic of a vibratory soil compactor with a vibratory roller at its front-axle.

The ride vibration properties of various work vehicles have been widely characterized and assessed in view of the WBV exposure and the associated potential risks. Only limited efforts, however, have been made in characterizing the ride vibration environment of soil compactors. The soil compactors are often perceived as tools or equipment rather than vehicles with a human operator and, thereby, a relatively lesser emphasis has been placed on the ride dynamics and vibration exposure of the operator. A few studies have reported the magnitude of WBV transmitted to the operators of the compactors. The reported levels, however, differ greatly, mostly due to different types of compactors considered in the studies. Dupuis et al. (1987) reported that the magnitude of frequency-weighted rms acceleration due to vertical vibration of a range of compactors vary from 0.3 to 1.7 m/s^2. The study also suggested that the compactor operators could be exposed to levels of WBV that exceed the limits considered safe as per the ISO-2631-1 (1997) guidelines for an eight-hour working day. A study in Europe (Griffin et al., 2006) has reported average exposure level of soil compactors in the order of 0.6 m/s^2, which exceeds the 'exposure action level' of 0.5 m/s^2 defined in the EC Directive (EN 2002/44/EC, 2002). The study also reported the vibration exposure level of 1.2 m/s^2 of the worst machine, which is beyond the 'exposure limit level' of 1.15 m/s^2 defined in the EC Directive. A study in the US reported the exposure in terms of vector sum of vertical, longitudinal and lateral vibration of 2.5 m/s^2 for a Caterpillar compactor (Beck et al., 2004). Another study in Ontario involving three different soil compactors has shown mean frequency-weighted vertical acceleration of 0.91 m/s^2, while the extreme level was 1.3 m/s^2 (Cann et al., 2003).

The magnitude of vibration transmitted to the operator is dependent upon many design and operating factors in a highly complex manner. These include: the vehicle weights and dimensions; load distributions; vehicle power; drum and cabin mounts/suspension; seat suspension; operating speed; soil/terrain properties; and more. The above reported studies considered a wide range of compactors, while their weights, dimensions and the operating conditions were not clearly defined. The reported ranges of the exposure levels are not likely to be considered applicable for the types of soil compactors typically employed in Québec (10- and 13-ton). Furthermore, the vibration transmitted to the operator is most notably affected by the mode of operation. During compaction, the vehicle operates at a very low speed, in the order of 3 km/h, with the roller vibrator on. The magnitude of ride vibration arising from the tire- and roller-terrain interactions would thus be expected to be small, while that due to the rotating unbalance would predominate at higher frequencies corresponding to the angular speed of the vibrator (25-35 Hz) and its multiples. The vibration environment during the compaction mode could thus be characterized by relatively high frequency vibration, which would be effectively attenuated by the frequency-weighting functions defined in ISO-2631-1. During travel within and across the worksites, the roller vibration is turned off and the vehicle operates at relatively higher speeds (10-12 km/h). The ride vibration environment in this mode is dominated by the low frequency translational and rotational vibration arising from the interactions of the tires and the drum with the rough terrain. The vibration exposure during the travel mode would thus be of primary concern in view of its potential effects on the working efficiency and well-being of compactor operators.

The asymmetric design of soil compactors, their operation on relatively rough terrains together with the lack of knowledge of their WBV properties, particularly for the machines employed in Québec, were the key motivating factors for this project. This report presents the experiment design used for the characterization of translational and rotational WBV environment of selected soil compactor models that are widely used in Québec, while operating on a test track and at selected worksites. The measured data are used to determine the vibration exposure, which is assessed using the ISO-2631-1 and EC guidelines. The vibration properties of the vehicle are further applied to recommend adequate design modifications or interventions for reducing the vibration exposure of the operators.

2. OBJECTIVES OF THE STUDY

The overall goal of the project is to contribute towards enhancement of whole-body vibration (WBV) environment of vibratory soil compactors used in the road building sector in Québec, in order to minimize the health and safety risks among the operators of such compactors. The specific objectives are summarized below:

- Identify predominant ride frequencies and effects of different operating conditions through measurements of vibration of soil compactors on a test track under controlled operating conditions;
- Characterize WBV environment of soil compactors that are most commonly used in Québec through field measurements at selected worksites;
- Assess the vibration exposure of the operators in accordance with the ISO-2631-1 and EC guidelines;
- Derive spectral classes of vibration corresponding to the most important modes of operation that could be applied to seek desired interventions; and
- Propose further directions for identifying effective interventions or design modifications to limit the operator exposure.

3. MEASUREMENTS OF VIBRATION

Test series were designed to measure translational as well as rotational vibration responses of soil compactors during two distinct operating modes: transit and compaction. These test series focused on vehicle models that are most commonly used by the construction industry in Québec. Consultations with the Canadian Association of Equipment Distributors (CAED), Sintra, SMS Équipement Fédéral and Hewitt, revealed that over 1000 soil compactors presently operate in Québec, the majority being single-drum compactors. Of these, nearly 50% are manufactured by Dynapac, 25% by Caterpillar and the remaining 25% by Ingersoll Rand, Bomag, and others. Moreover, the majority of the soil compactors in Québec are of 10- or 13-ton capacity. The two leading manufacturers (Dynapac and Caterpillar) were subsequently contacted to obtain information relevant to vehicle design and WBV emission values, if available, and to seek their support in facilitating the field measurements. Both manufacturers expressed limited knowledge of vibration responses of the vehicles employed in Québec, while Caterpillar declined to participate in the study. The study was subsequently focused on two 10-ton compactor models propelled by 4- and 6-cylinder engines, denoted by ‘10-ton 4-cylinder’ and ‘10-ton 6-cylinder’ machines, respectively; as well as a 13-ton compactor model propelled by a 6-cylinder engine denoted by ‘13-ton 6-cylinder’. These machines were considered to be most representative of the compactors being used in Québec.

Two test series involving different vehicles were undertaken. The first series involved measurements on a test track under controlled conditions, while the second series was designed to measure vibration on worksites. The detailed test series are presented in the following subsections.

3.1 Measurements of Vibration on a Test Track

Two 10-ton compactors (’10-ton 4-cylinder’ and ’10-ton 6-cylinder’) were employed in the first test series for measurements of vibration during both the compaction and the transit modes. The primary objective was to identify predominant ride frequencies of the vehicles under controlled operating conditions on a test track. The chosen vehicles were quite similar in their weights and dimensions but differed in engine power. Both vehicles were equipped with articulated frame steering, an open platform (cabin) and a cushion (unsuspended) seat. It should be noted that a closed driver enclosure or cabin is often retrofitted to these vehicles in order to adapt to the weather conditions in Québec. The front unit supported the drum through a number of elastic mounts. The drum in each vehicle was equipped with eccentric masses rotating at approximately 2000 RPM, which could generate two different amplitudes of vibration (‘low’ and ‘high’). The cabin structure and the engine were supported by the rear unit of the vehicle through elastic mounts.

The tests were performed on a test track at the Dynapac’s test facility in Selma, TX, to measure vehicle vibration during simulated compaction and transit tasks. The test track (Figure 3.1) offered desired courses for simulated transit and compaction tasks. In the compaction mode, the vehicles were operated on levelled deformable soils at a speed near 3 km/h in the forward and backward directions. Compactions were performed on selected soils of different density (low density humid soil; high density dry soil; and very high density gravel) at two different amplitudes of roller vibration, although the majority of them were performed with the vibrator set at ‘high’ amplitude. Each compaction run corresponding to ‘low’ and ‘high’ amplitude settings on the selected soil was repeated a few times, depending upon the weather condition and the deformability of the surface. In the transit mode, the compactors were driven on non-deformable track segments longer than 100 m at a nearly constant forward speed of 10 km/h. The vibrator was set to ‘off’ position. The road surface roughness of the test track was judged to be ‘average’, which would be representative of the secondary roads in Québec. The test series involved a total of 23 and 27 runs for the 10-ton 4-cylinder and the 10-ton 6-cylinder compactors, respectively. Table 3.1, as an example, summarizes different runs for the 10-ton 6-cylinder compactor. The test series also included runs with engine idling for a verification of the sensors' signals.

Figure 3.1: View of the test track used for measurements during compaction and transit modes.

3.1.1 Vehicle instrumentation

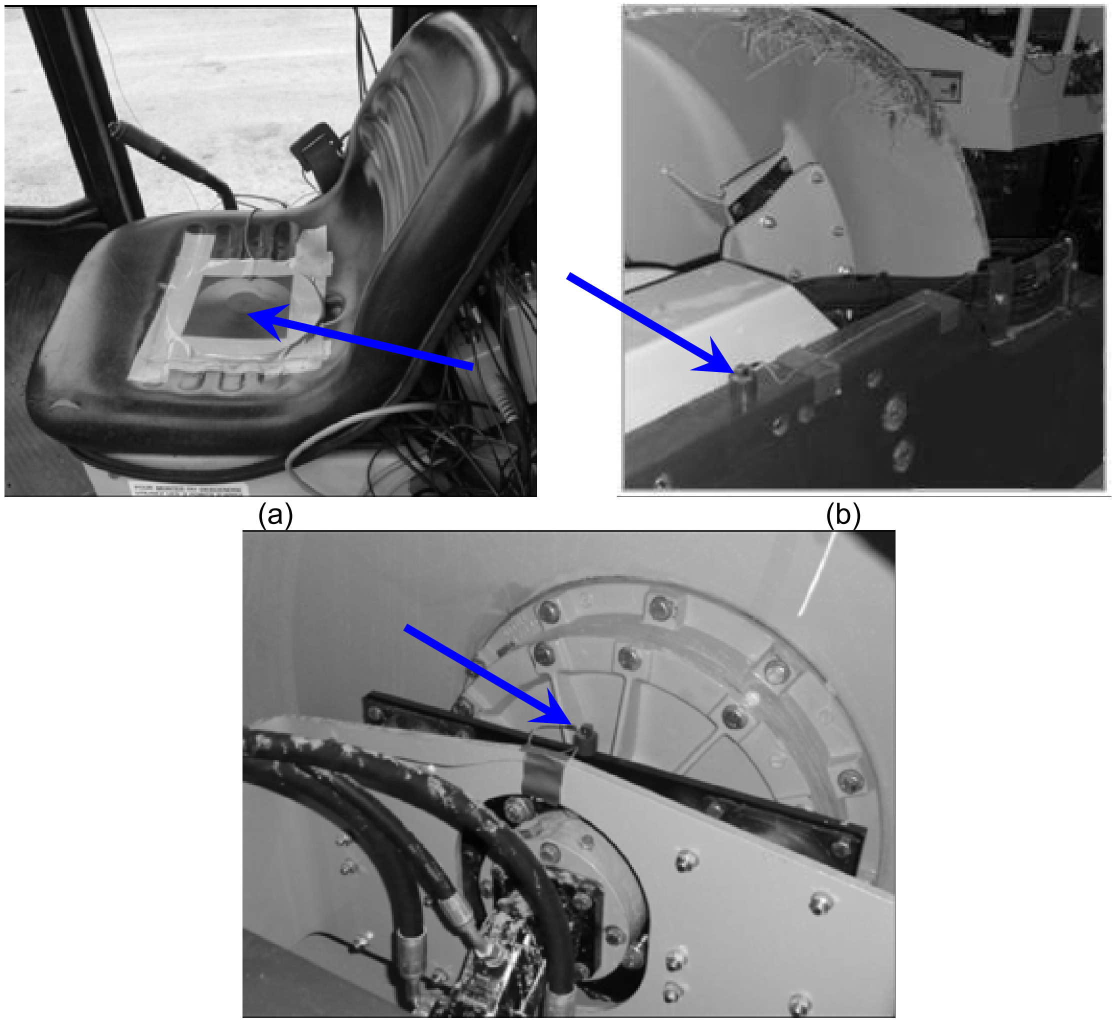
Each test vehicle was instrumented to measure vibration responses of the four primary bodies of the vehicle, namely the seat, the open cabin (operator station), the drum, and the main vehicle body, or the rear frame. These included:

- A 3-axis seat accelerometer (ADXL05JH, ±5g) installed on the seat cushion for measurements of longitudinal (x), lateral (y) and vertical vibration at the operator/seat interface, as shown in Figure 3.2(a);
- A 3-axis gyro coupled with a 3-axis accelerometer (IMU400CC, ±100º/s) installed on the open cabin floor near the operator seat to measure translational and rotational vibration of the cabin/platform;
- A 3-axis gyro coupled with a 3-axis accelerometer (IMU400CC, ±200º/s) installed on the rear unit frame, close to the vehicle body mass center, for measurements of translational and rotational vibration of the main vehicle body (frame);
- A 3-axis accelerometer (Crossbow CXL10GP3, ±10g) mounted on the rear frame above the bolted joint of the rigid axle. Only the vertical acceleration was acquired with this accelerometer since the horizontal vibration was expected to be similar to that of the vehicle body;
- A 3-axis accelerometer (PCB Piezotronics, ±50g) mounted on the drum-propelling side (hydrostatic transmission) of the front frame, in-plane with the drum axis for measurements of translational vibration transmitted by the drum to the front frame through the elastic mounts (Figure 3.2(b)). Only the x- and z-axis acceleration signals were acquired; and
- A 3-axis accelerometer (PCB Piezotronics, ±50g) attached to the vibrator motor bracket of the drum to measure the drum acceleration along the x- and z-axis (Figure 3.3(c)).

Table 3.1: Summary of test runs for measurements of vibration responses of the 10-ton 6-cylinder soil compactor.

Run #	Operation	Soil Density	Vibrator	Speed (km/h)	Direction
1	Transit #1	Non-deformable	Off	10	Forward
2	Engine idling #1	Non-deformable	Off	0	N/A
3	Compaction/humid soil #3	Low density	High	3	Forward
4	Compaction/humid soil #3	Low density	High	3	Backward
5	Compaction/humid soil #1	Low density	High	3	Forward
6	Compaction/humid soil #1	Low density	High	3	Backward
7	Compaction/humid soil #2	Low density	High	3	Forward
8	Compaction/humid soil #2	Low density	High	3	Backward
9	Transit #2	Non-deformable	Off	10	Forward
10	Compaction / gravel	Very high density	High	3	Forward
11	Compaction / gravel	Very high density	Low	3	Backward
12	Transit over obstacles	Non-deformable	Off	10	Forward
13	Transit over obstacles	Non-deformable	Off	10	Backward
14	Transit over obstacles	Non-deformable	Off	5	Forward
15	Transit over obstacles	Non-deformable	Off	5	Backward
16	Transit #3	Non-deformable	Off	10	Forward
17	Compaction/ dry soil #1	Over-compacted	High	3	Forward
18	Compaction/ dry soil #1	High-density	High	3	Forward
19	Compaction/ dry soil #1	High-density	High	3	Backward
20	Compaction/ dry soil #1	Over-compacted	High	3	Backward
21	Engine idling #2	Non-deformable	Off	0	N/A
22	Compaction/ dry soil #2	Over-compacted	Low	3	Forward
23	Compaction/ dry soil #2	High-density	Low	3	Forward
24	Compaction/ dry soil #2	High-density	High	3	Backward
25	Compaction/ dry soil #2	Over-compacted	High	3	Backward
26	Engine idling #3	Non-deformable	Off	0	N/A
27	Transit #4	Non-deformable	Off	10	Forward

The signals from the PCB accelerometers were conditioned using a signal conditioner/amplifier, while those from the gyros and seat micro-accelerometers (Crossbow) were directly acquired in a multi-channel data recorder (TEAC). It should be noted that the gyros provided the measures of the angular velocities, which were subsequently differentiated during data analysis to derive angular accelerations. All measurement systems were calibrated in the laboratory prior to their installation.



(a) (b) (c)

Figure 3.2: (a) Seat accelerometer; (b) accelerometer located on the front-frame; and (c) accelerometer located on the drum group (vibrator motor bracket).

3.2 Measurements of Vibration at Worksites

The second test series involved measurements of vibration under most representative work conditions at two different worksites. These included an urban development worksite in Joliette (Québec) and a highway development site near Trois-Rivières (Québec). Different vehicles were chosen for each worksite, which included:

(i) A 10-ton compactor that is most commonly used by the Quebec construction industry. This compactor was 7 years old (1800 hours) and comprised a modified driver enclosure (cabin) replacing the original open-platform, and an unsuspended driver seat. It is not known if the cab mounts were redesigned in accordance with the weight of the modified enclosure. It was powered by a 4-cylinder engine. The chosen vehicle was considered by operators as “average” from a WBV standpoint. It was also considered to represent an average compactor in view of its capacity and age, and is denoted by ‘10-ton 4-cylinder’ hereafter. The vibration properties of this vehicle were measured on an urban development worksite.

(ii) A 13-ton compactor with a manufacturer supplied operator cabin and cabin mounts, and a suspension seat. It was powered by a 6-cylinder engine. This compactor was only 2 years old (600 hours), was considered as one of few equipment representing an "acceptable" level of WBV and was considered to represent the best design in view of the vibration isolation performance. It is denoted by '13-ton 6-cylinder' hereafter. The vibration properties of this vehicle were measured on a highway development worksite.

The tests were performed at the worksites during the compaction and transit tasks. The compaction runs involved repeated passes over two different lanes (denoted as lanes '1' and '2') of the road surface, while the travel runs were performed during transit form the worksites to holding stations. The compaction runs for the 10-ton 4-cylinder machine comprised 6 and 8 passes on lanes '1' and '2', respectively. The 13-ton 6-cylinder machine performed 7 and 5 runs on lanes '1' and '2', respectively. The responses during the transit mode were measured over 5 and 2 runs for the 10- and 13-ton compactors, respectively. It needs to be mentioned that the nature of the transmitted vibration would vary considerably with the increasing number of passes on a given lane. This is attributable to increase in the stiffness and density of the soil being compacted, and possible variations in amplitude of the vibrator. Although, it is generally desirable to employ 'low' amplitude compactor vibration during the final passes on a given lane, a definite pattern of the selection of vibration amplitude could not be observed during measurements. The operator of the 13-ton 6-cylinder machine chose to conduct all the compaction runs with the vibrator set at 'low' amplitude, while the operator of the 10-ton 4-cylinder machine varied the amplitude in a more or less arbitrary manner. Table 3.2 summarizes the various compaction and transit runs considered, together with the chosen vibrator amplitude and direction of travel.

Table 3.2: Summary of test runs for measurements of vibration responses of the compactors at the two worksites.

	10-ton 4-Cylinder Compactor			*13-ton 6-Cylinder Compactor*		
Mode (pass)	Run #	Amplitude	Direction	Run #	Amplitude	Direction
Transit (1)	1	-	Forward	1	-	Forward
Transit (2)	2	-	Forward	2	-	Forward
Transit (3)	3	-	Forward		-	
Transit (4)	4	-	Forward		-	-
Transit (5)	5	-	Forward		-	-
Compaction Lane ‘1’ (1)	6	High	Forward	3	Low	Forward
Compaction Lane ‘1’ (2)	7	High	Backward	4	Low	Backward
Compaction Lane ‘1’ (3)	8	Low	Forward	5	Low	Forward
Compaction Lane ‘1’ (4)	9	Low	Backward	6	Low	Backward
Compaction Lane ‘1’ (5)	10	High	Forward	7	Low	Forward
Compaction Lane ‘1’ (6)	11	Low	Backward	8	Low	Backward
Compaction Lane ‘1’ (7)				9	Low	Forward
Compaction Lane ‘2’ (1)	12	Low	Forward	10	Low	Forward
Compaction Lane ‘2’ (2)	13	Low	Backward	11	Low	Backward
Compaction Lane ‘2’ (3)	14	High	Forward	12	Low	Forward
Compaction Lane ‘2’ (4)	15	High	Backward	13	Low	Backward
Compaction Lane ‘2’ (5)	16	High	Forward	14	Low	Forward
Compaction Lane ‘2’ (6)	17	High	Backward			
Compaction Lane ‘2’ (7)	18	High	Forward			
Compaction Lane ‘2’ (8)	19	Low	Backward			

3.2.1 Vehicle instrumentation

Unlike the tests performed on the test track, the vehicle instrumentation in these tests was mostly limited to the cabin and the seat for the purpose of exposure assessment and for identifying a desirable intervention. The vibration of the rear frame was also monitored during both transit and compaction modes. The instrumentation used for each test vehicle is summarized below:

- A 3-axis seat accelerometer (ADXL05JH, ±5g) installed on the seat cushion for measurements of longitudinal (x), lateral (y) and vertical (z) vibration at the operator/seat interface, as shown in Figure 3.2(a);
- A 3-axis gyro coupled with a 3-axis accelerometer (IMU400CC, ±100º/s) installed on the cabin floor near the operator seat to measure translational and rotational vibration of the cabin/platform;
- A 3-axis accelerometer (PCB Piezotronics, ±50g) installed on the rear frame, close to the vehicle body mass center, for measurements of translational vibration of the vehicle body.

3.3 Data Analyses

The acquired data segments for each test vehicle were grouped for each mode of operation, namely transit and compaction. The data acquired on the test track were grouped for compaction of lower- and higher-density soils alongside the transit trials. For this case, each operation comprised between 3 to 6 data segments of varying lengths, as summarized below:

- 10-ton 4-cylinder, transit mode (10 km/h): 5 segments of 120 seconds each
- 10-ton 6-cylinder, transit mode (10 km/h): 4 segments of 120 seconds each
- 10-ton 4-cylinder, compaction (high density): 3 segments of 60 seconds each
- 10-ton 6-cylinder, compaction (high density): 3 segments of 60 seconds each
- 10-ton 4-cylinder, compaction (low density): 3 segments of 120 seconds each
- 10-ton 6-cylinder, compaction (low density): 6 segments of 120 seconds each

The vibration data acquired during different compaction passes on a given lane at the worksite were examined in order to evaluate the effects of increasing soil stiffness with increasing number of passes. The data acquired during several compaction and transit runs were subsequently grouped in a manner similar to that described for the test-track trials. Furthermore, the data acquired under 'low' and 'high' vibrator amplitudes were grouped together since a definite pattern on amplitude could not be established.

The measured data were processed through a 0.7 Hz cut-off frequency high-pass filter to eliminate the signal bias, if any, and digitized using Brüel & Kjær PULSE analyser platform. The data were subsequently analyzed to determine the spectra of measured vibration responses in terms of power spectral density (PSD) using a bandwidth of 100 Hz (frequency resolution of 0.125 Hz) and rms acceleration in the third-octave frequency bands. The data acquired during the worksite runs were further analyzed to determine the frequency-weighted rms accelerations along individual axes and vector sum rms acceleration during compaction and transit tasks, in accordance with the method defined in ISO-2631-1 (1997). Eight hour equivalent exposure was also computed by combining the exposures during compaction and transit, which was assessed and discussed in view of the EC guidelines.

4. CHARACTERIZATION OF VIBRATION AND EXPOSURE ASSESSMENTS

The measured data acquired during the two test series were analyzed to characterize the vibration transmission properties of the vehicles and to assess the vibration exposure of the operators. The measured data acquired on the test track generally revealed a considerably higher magnitude of vibration along the translational as well as rotational axes compared to the data acquired during the worksite runs. This was attributed to relatively higher speeds used during the test track runs, which resulted in frequent jumping of the drum from the road surface. The results attained from the measurements performed on the test track were thus not used to assess the WBV exposure. These results were, however, considered vital for determining the vibration properties of the vehicle, particularly the dominant frequencies of vibration, and the relative magnitude of vibration along the longitudinal (x), lateral (y), vertical (z), roll (φ) and pitch (θ) axes. The vibration level along the yaw-axis was observed to be considerably small during both the compaction and transit tasks, and could be directly associated with the turning manoeuvres of the vehicle. The yaw vibration responses of the machines were thus excluded from further analyses. The resulting spectra and the dominant ride frequencies could then be applied to obtain estimates of the vehicles' natural frequencies and to seek effective interventions. The assessment of vibration exposure was performed using the data acquired at the worksites, which is considered to be representative of the work conditions.

The measured vibration data acquired at the worksites revealed low crest factors (well below 9), while the crest factors of the data acquired at the test track were below 12. The exposure analyses of the measured data acquired at the worksites were thus limited to unweighted and frequency-weighted rms accelerations in accordance with ISO-2631-1(1997) and the EC guidelines (2002).

4.1 Characterization of Vibration Properties of Vehicles

The acceleration spectra of various transit and compaction mode runs on the test track were evaluated for each compactor, which were subsequently used to identify dominant ride frequencies and probable modes of vibration. The results were obtained in terms of acceleration power spectral density (PSD) and one-third octave band rms spectra of accelerations along the translational and rotational axes. The vibration characteristics of the vehicles under different operating conditions are presented in terms of acceleration PSD, while the rms spectra are applied to derive overall unweighted and frequency-weighted rms accelerations. The spectra of acceleration of the related segments or repeated runs for each operating mode were grouped together to define the ranges of vibration. The ranges identified for the measurements obtained at the cabin/platform floor were subsequently used to establish the spectral classes of vibration. Furthermore, the acceleration spectra of both vehicles were quite comparable in magnitude and frequencies, except for slight differences in the roll mode frequencies, which were attributed to different load distributions (rear unit) of the vehicles.

The spectra of acceleration obtained for runs corresponding to each mode of operation generally revealed comparable trends in the dominant frequencies corresponding to peak vibration magnitude. These frequencies could thus be associated with natural frequencies and vibration modes of the vehicles. Figure 4.1, as an example, illustrates comparisons of vertical acceleration PSD measured at the vehicle rear frame (denoted as vehicle body hereafter) over five different transit runs at a forward speed near 10 km/h. The comparison suggests reasonably good repeatability of the runs, particularly in view of the dominant frequencies of vibration, although considerable deviations in magnitude are evident. These are attributable to possible variations in speed and local road roughness. Similar degrees of repeatability were also observed in the measurements obtained for different compaction runs for each soil density considered. Owing to the observed repeatability, the data attained during different runs for the same operation were subsequently grouped to characterize vibration properties by the mean and range of acceleration PSD and rms acceleration magnitude. The resulting envelops of spectra discussed in the following subsection could be applied for vehicle model verifications, vibration dosage assessments and design or tuning of secondary suspensions at the cabin and the seat.

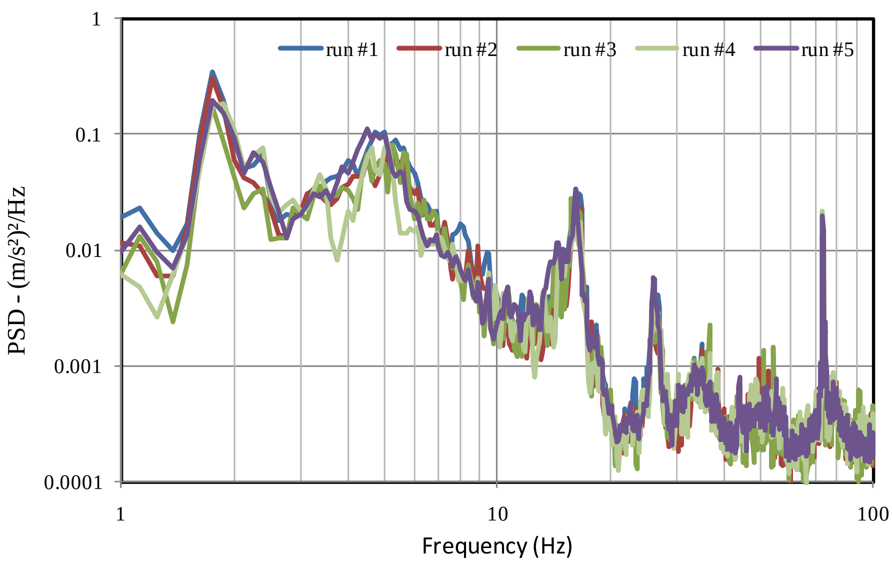
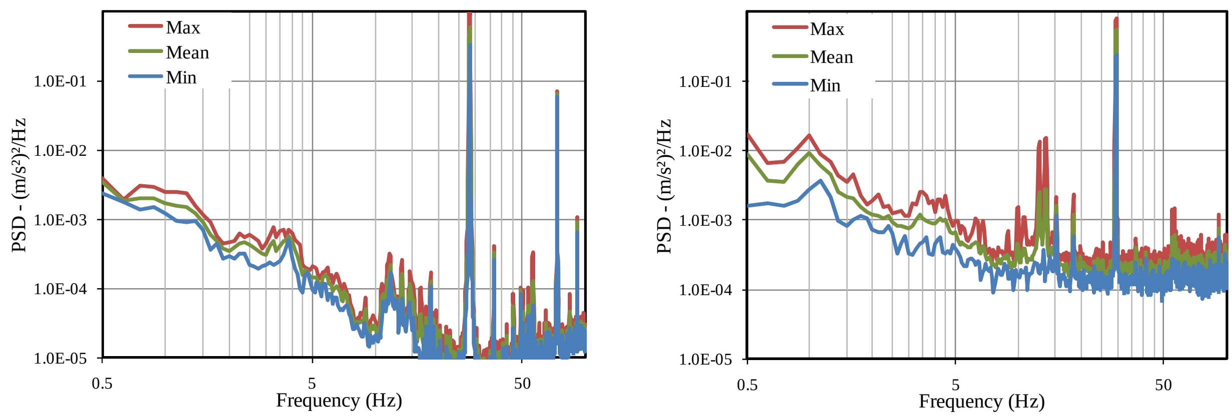


Figure 4.1: Comparison of PSD of vertical acceleration measured at the rear frame (vehicle body) of the 10-ton 4-cylinder vehicle during 5 different transit runs.

4.1.1 Vibration Characteristics during Low-Density Soil Compaction

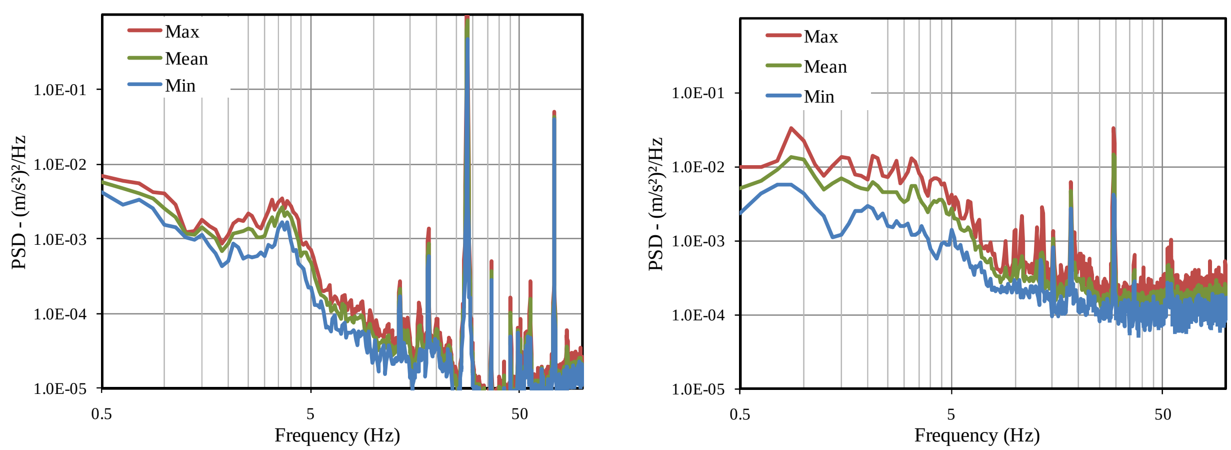
Soil compaction is invariably performed at very low speeds (nearly 3 km/h). The resulting vibration amplitude caused by tire/drum–terrain interactions would thus be expected to be small. The eccentric mass vibrator, however, tends to introduce high magnitude vibration at a relatively higher frequency, near 30 Hz. Such vibration during compaction, particularly involving low density soil or low amplitude vibrator operation, is not considered to be of concern since the frequency-weightings defined in ISO-2631-1 tend to greatly suppress the contribution due to high frequency vibration. The ranges of acceleration PSD due to vibration measured at the cabin floor of the two vehicles along the x, y, z, θ and φ directions, are presented in Figs. 4.2 to 4.6, respectively, while those measured at the seat and the vehicle body are presented in Appendix A (Figs. A.1 to A.5).

The results clearly show a distinct high magnitude peak near 30 Hz, irrespective of the machine and of the location and direction of the measured vibration. The spectra also reveal peaks at multiples of the fundamental eccentric mass excitation frequency of approximately 30 Hz. These are clearly evident in the spectra of vibration measured at the cabin floor and at the vehicle body near 15, 60 and 90 Hz. The results, in general, exhibit very low magnitude of low frequency (<10 Hz) translational and rotational vibration, while the 10-ton 6-cylinder machine yields slightly higher magnitudes of such vibration. The vibration exposure and the associated potential risks are thus not expected to be of concern in this mode of operation. Furthermore, the drum and cabin mounts tend to greatly attenuate the high frequency vibration caused by the vibrator for both machines, although these mounts appear to be more effective for the 10-ton 6-cylinder machine. This is most likely attributed to differences in the inertial and mass distribution properties of the two vehicles. Both the roll and pitch acceleration spectra tend to increase with frequency, as shown in Figures 4.5 and 4.6, which is mostly attributed to very low level bending and torsional displacements of the vehicle body and cabin structure. A few studies reporting angular vibration of heavy vehicles have also shown similar trends and attributed higher angular vibration at higher frequencies to structural deformation modes (Boileau et al., 2005; Rakheja et al., 2001).



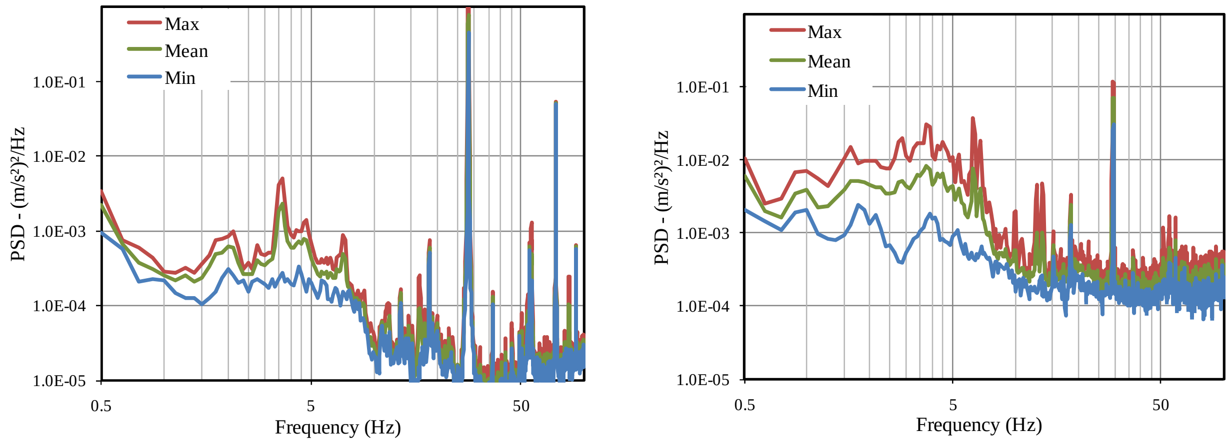
(a) **(b)**

Figure 4.2: Ranges of PSD of longitudinal (x) acceleration measured at the cabin floor during low-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



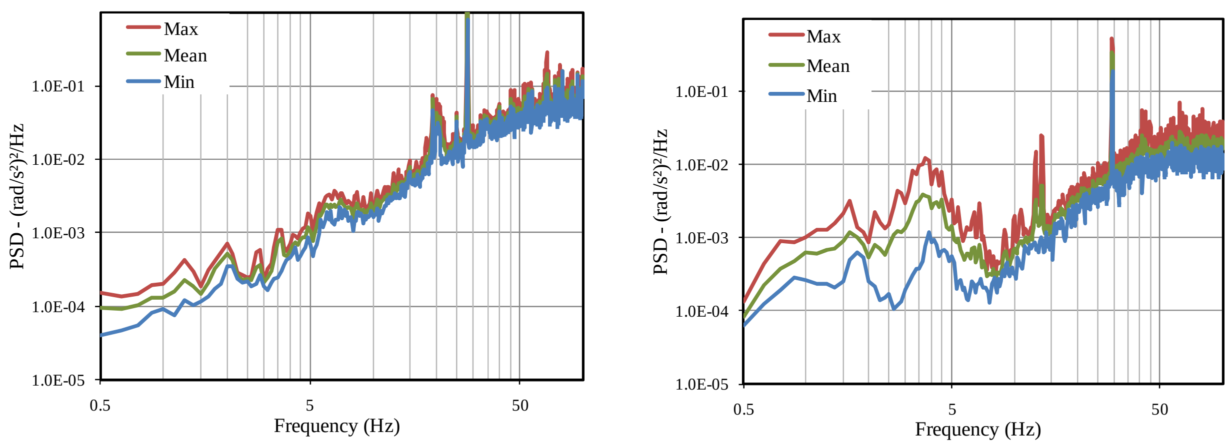
(a) **(b)**

Figure 4.3: Ranges of PSD of lateral (y) acceleration measured at the cabin floor during low-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



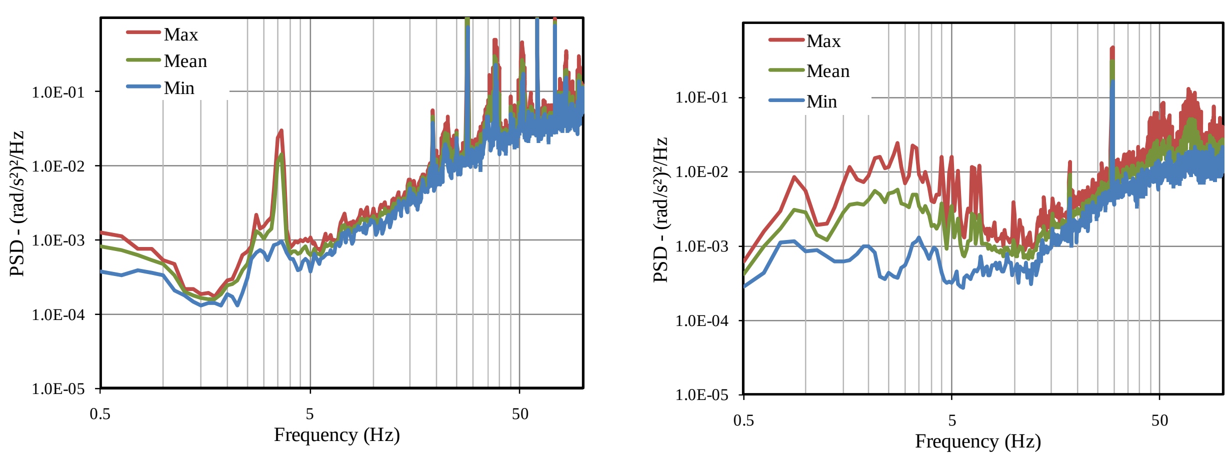
(a) **(b)**

Figure 4.4: Ranges of PSD of vertical (z) acceleration measured at the cabin floor during low-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



(a) **(b)**

Figure 4.5: Ranges of PSD of pitch (θ) acceleration measured at the cabin floor during low-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.

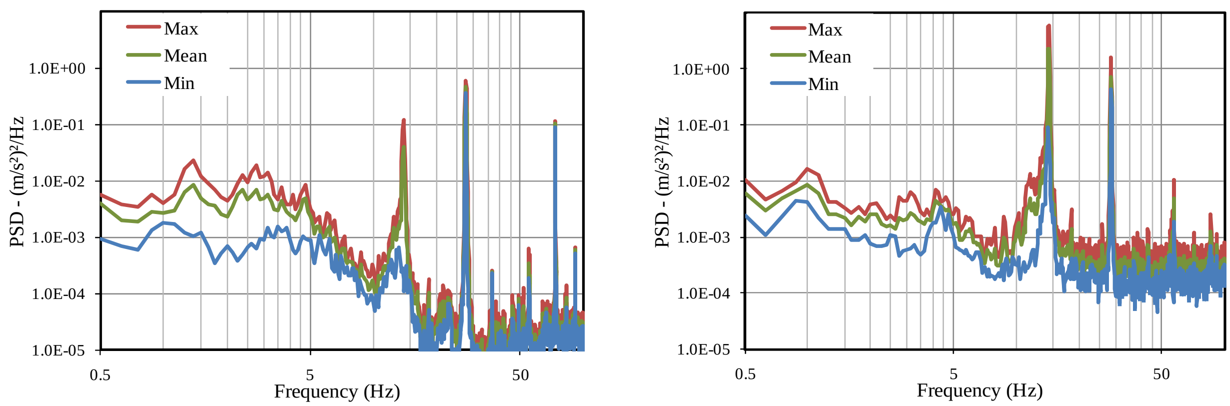


(a) **(b)**

Figure 4.6: Ranges of PSD of roll (φ) acceleration measured at the cabin floor during low-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.

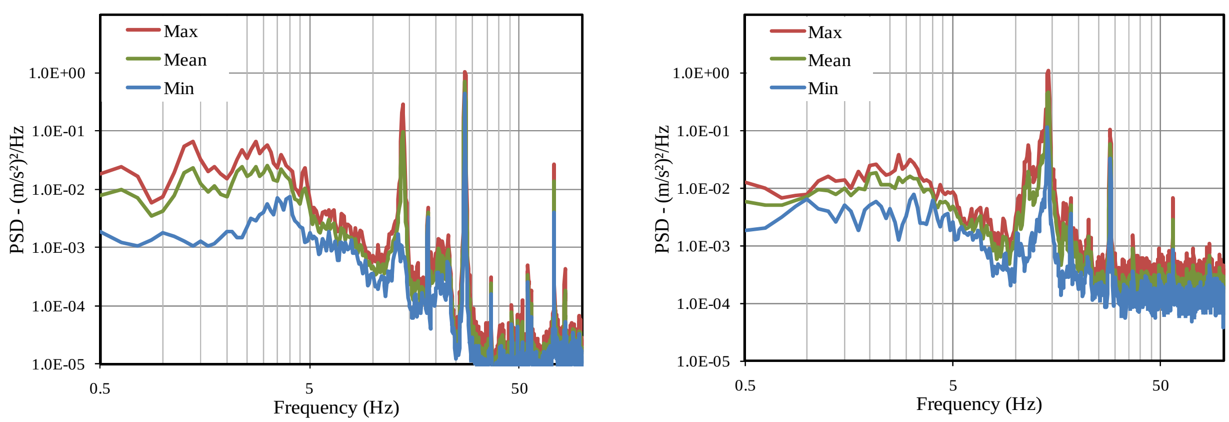
4.1.2 Vibration Characteristics during High-Density Soil Compaction

Soil density tends to increase with repeated passes of the compactor on a given terrain surface, which enhances dynamic interactions of the drum and the tire with the terrain due to greater stiffness of the soil. Vehicle operation on dense soils may also yield partial or total intermittent hopping motion (loss of drum-soil contact) of the drum (Adam and Kopf, 2000; Andereg, 2000), leading to higher magnitudes of transmitted vibration. The magnitude of low frequency vibration along the x-, y- and z-axis of both vehicles was observed to be higher than that measured during low-density soil compaction, as shown from the spectra of vibration measured at the cabin floor, presented in Figures 4.7 to 4.9. The ranges of spectra of vibration measured at the seat and vehicle body are presented in Appendix A (Figs. A.6 to A.10).



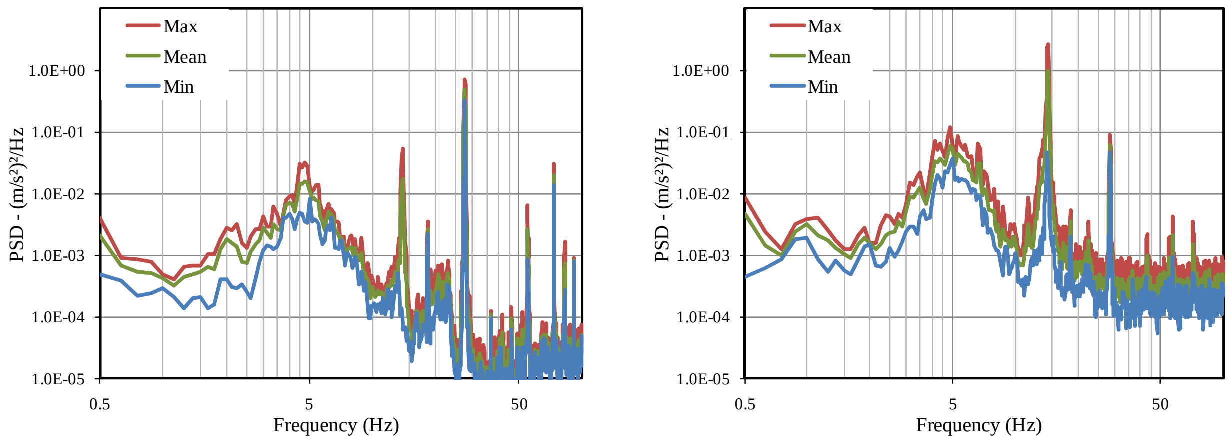
(a) **(b)**

Figure 4.7: Ranges of PSD of longitudinal (x) acceleration measured at the cabin floor during high-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



(a) **(b)**

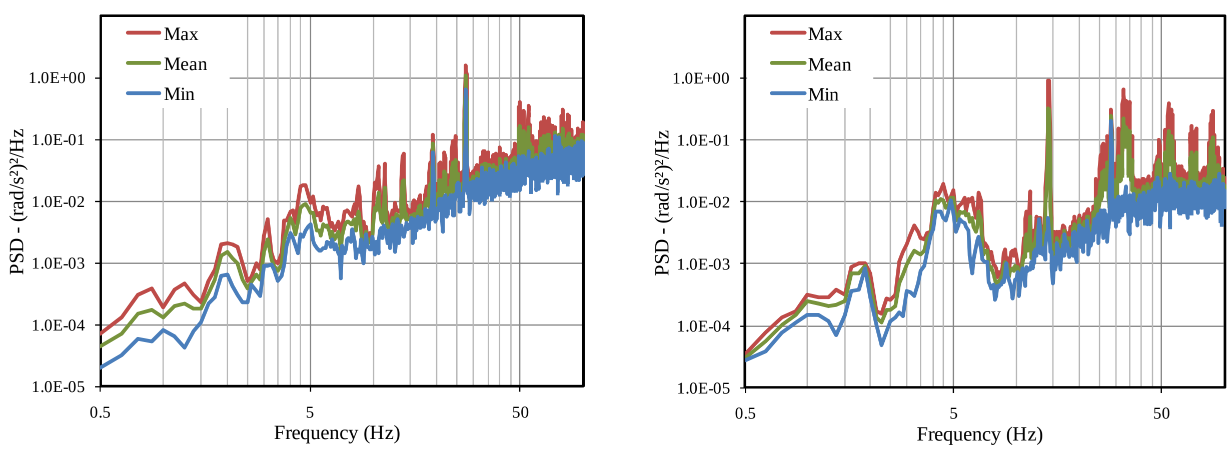
Figure 4.8: Ranges of PSD of lateral (y) acceleration measured at the cabin floor during high-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



(a) **(b)**

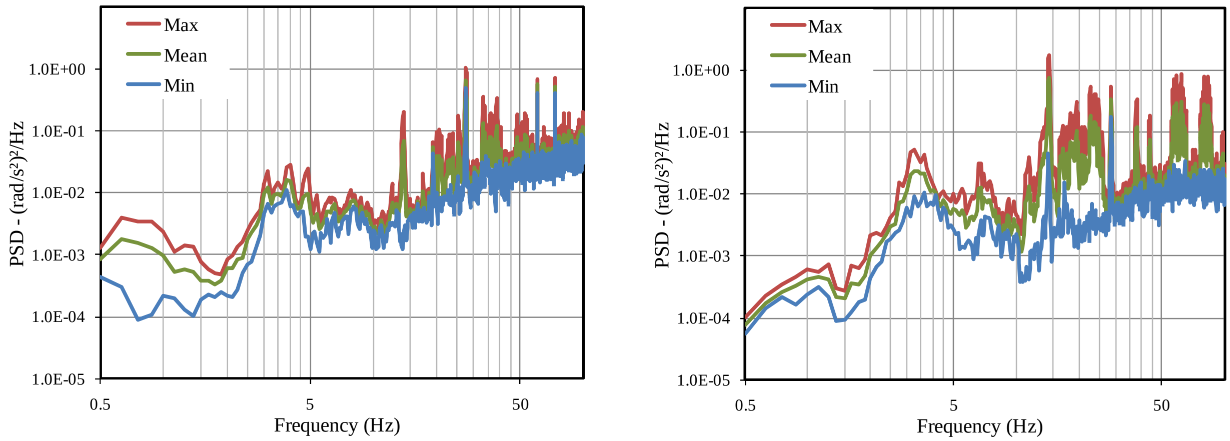
Figure 4.9: Ranges of PSD of vertical (z) acceleration measured at the cabin floor during high-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.

The spectral components of low frequency vibration, however, are quite similar to those observed under low density soil compaction. The compaction of higher density soil tends to emphasize the peaks at 15 Hz (one-half the frequency of the rotating unbalance), as seen in the figures. This is believed to be caused by the hopping motion of the drum on the relatively hard soil. The magnitude of longitudinal and lateral vibration near 15 Hz tends to be higher than that observed at the fundamental frequency of approximately 30 Hz. The hopping motion of the drum may also contribute to the excitation of some of the low frequency modes of the vehicle. The magnitude of low frequency vibration peaks in the 1.4 – 8.0 Hz range is thus higher than that observed in Figs. 4.2 to 4.4. Similar trends are also observed in the PSD of the pitch and roll accelerations of the vehicle body and the cabin as seen in Figures 4.10 and 4.11, respectively.



(a) **(b)**

Figure 4.10: Ranges of PSD of pitch (θ) acceleration measured at the cabin floor during high-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.

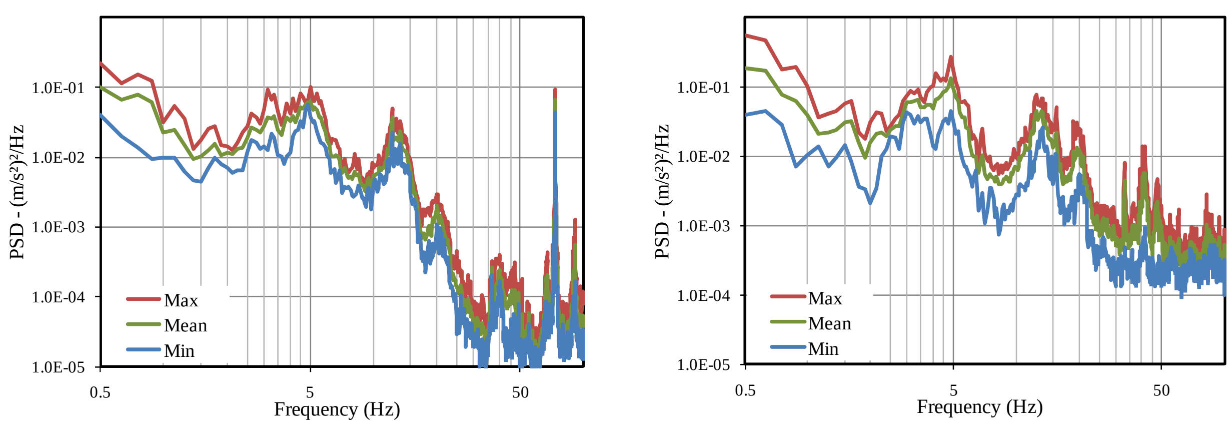


(a) (b)

Figure 4.11: Ranges of PSD of roll (φ) acceleration measured at the cabin floor during high-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.

4.1.3 Vibration Characteristics during Transit

In the transit mode, the vehicle operates with the vibrator turned off. The vibration behaviour of the vehicle is thus mostly determined by the drum/wheel interactions with the terrain surface. Furthermore, the vehicle speed is considerably higher than that in compaction, which would yield a considerably higher magnitude of vibration, particularly in the low frequency range. The frequencies of dominant low frequency vibration observed from the spectra of vibration measured during the transit were generally quite comparable with those observed in the data during the compaction modes for both vehicles. These frequencies could thus be considered as the natural frequencies of the vehicles. Figures 4.12 to 4.16 illustrate the ranges of spectra of longitudinal (x), lateral (y), vertical (z), pitch (θ) and roll (φ) acceleration, measured at the cabin floor, while the spectra for the acceleration measured at the seat and vehicle body are presented in Appendix A (Figs. A.11 to A.15).



(a) (b)

Figure 4.12: Ranges of PSD of longitudinal (x) acceleration measured at the cabin floor during transit: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.

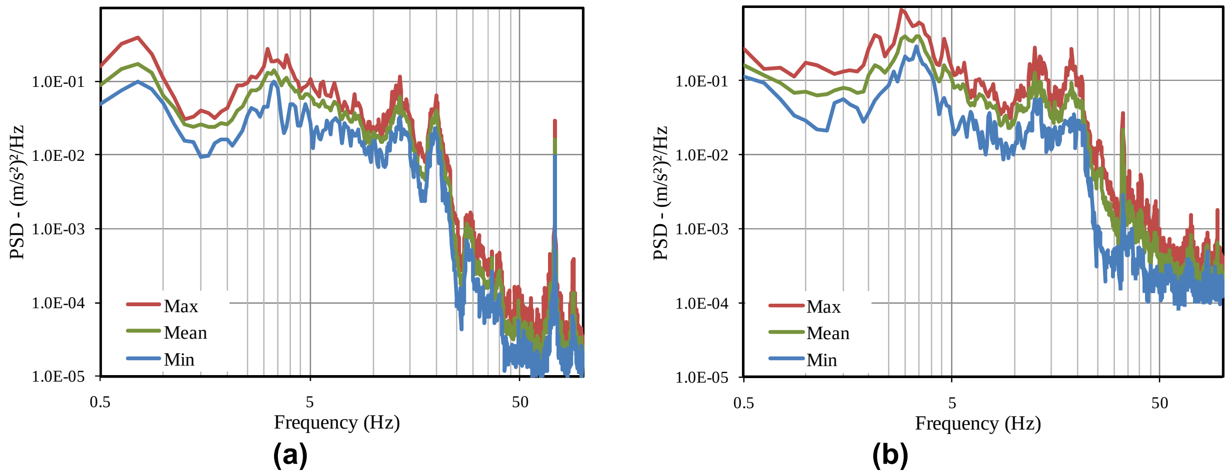


Figure 4.13: Ranges of PSD of lateral (y) acceleration measured at the cabin floor during transit: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.

The results show a considerably higher magnitude low frequency vibration in all the axes compared to that observed during the compaction mode. Furthermore, the high frequency vibration attributed to the vibrator is not evident, although the results also show significant levels of high frequency vibration, which were attributed to bending and torsional deflections of the vehicle and cabin structures. The acceleration spectra show peaks in the 1.4-2.4, 2.7-3.9, 4.2-8.0, 12-17 and 18.4-21.0 Hz. These peaks can generally be observed from the responses along all the axes, while the corresponding frequencies could be associated with particular modes of vibration of the vehicle. Furthermore, the ranges of vibration frequencies observed from spectra of vibration of the two vehicles are quite comparable.

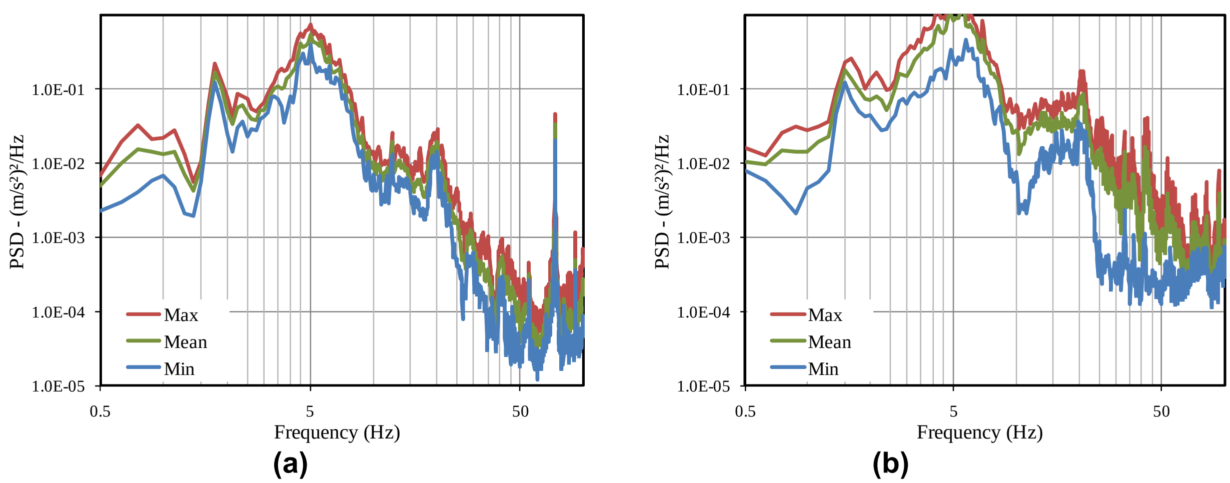
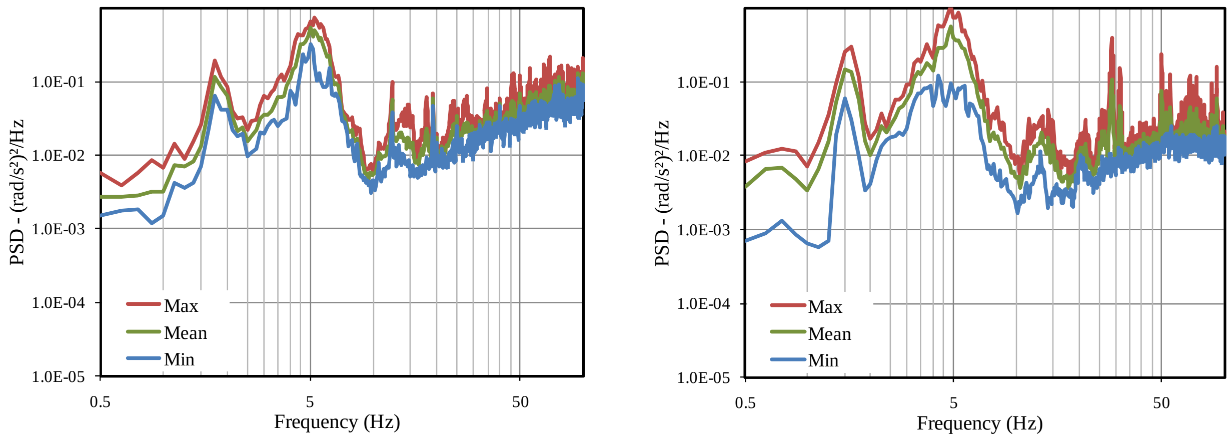
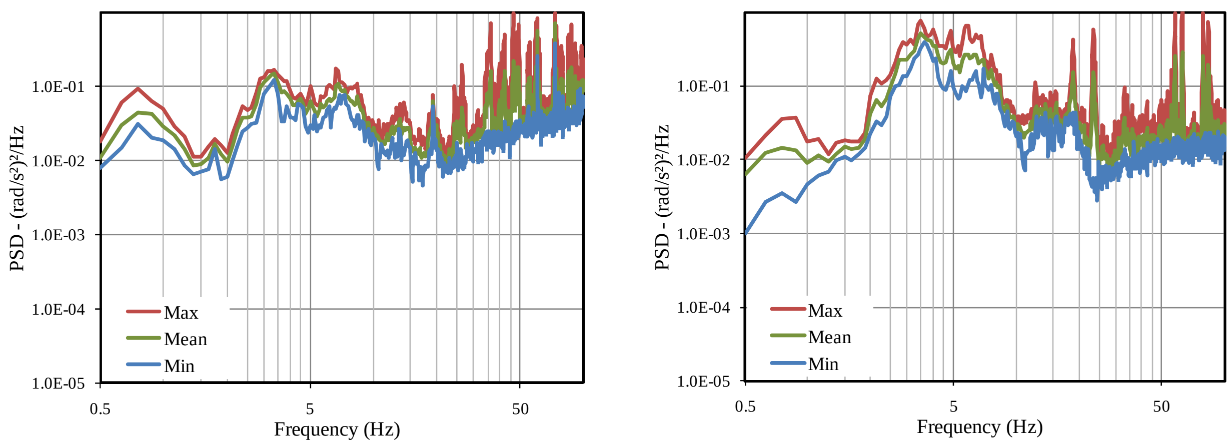


Figure 4.14: Ranges of PSD of vertical (z) acceleration measured at the cabin floor during transit: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



(a) **(b)**

Figure 4.15: Ranges of PSD of pitch (θ) acceleration measured at the cabin floor during transit: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



(a) **(b)**

Figure 4.16: Ranges of PSD of roll (φ) acceleration measured at the cabin floor during transit: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.

The ranges of pitch plane vibration spectra (x, z and θ) consistently reveal a distinct peak in the vicinity of 4.9 Hz. The magnitude of this peak is particularly pronounced in the pitch responses, but is also evident from the vertical and longitudinal acceleration spectra of the cabin and the seat. This peak is thus believed to be attributed to pitch vibration mode of the vehicle body. Considering that the mass and mass moment of the vehicle body are substantially larger than those of the cabin and the engine, a greater participation of the pitch mode in the responses of the other bodies can be expected.

The pitch plane vibration spectra also exhibit high magnitude peaks near 1.7 and 3.2 Hz in the vertical and longitudinal responses measured at the vehicle body. The cabin pitch spectra exhibit large peak near 4 Hz, while the cabin vertical vibration peaks near 5.5 Hz. The cabin acceleration spectra also exhibit peak longitudinal acceleration in the 12-13 Hz range, although this could also be associated with coupled lateral/yaw modes as the cabin floor sensor was mounted with some noticeable offset from the plane of vertical symmetry of the vehicle due to space constraints in the vicinity of the operator seat. The results clearly show coupled pitch plane vibration (x, z and θ) with peaks occurring near 1.7, 3.2, 4, 4.9 and 5.5 Hz. From the observed peaks, it is believed that the frequencies 1.7, 3.2 and 4.9 Hz are associated with the bounce, longitudinal and pitch modes of the vehicle body, respectively. The cabin pitch and bounce modes are speculated to occur near 4 and 5.5 Hz, respectively.

The measured acceleration spectra also show peaks at comparable frequencies in the bounce, roll and lateral axes suggesting coupling in the roll plane motions. The vehicle body roll acceleration spectrum exhibits distinct peak near 3.4 Hz, which is also evident in the cabin roll response. The roll mode of the rear frame of the vehicle is thus believed to occur near this frequency. The roll acceleration spectra of the cabin of both vehicles also exhibit distinct peaks near 6.8 Hz and in the 12-13 Hz frequency range. These frequencies are attributed to the roll mode of the cabin and its coupled lateral/yaw modes, respectively. Peaks near 2.2 and 3 Hz are also evident in the lateral acceleration spectra of the vehicle body, which correspond to its coupled lateral/yaw mode frequencies and are also evident in the lateral acceleration spectra of the cabin. The acceleration spectra also show peaks near 73 Hz, which seems to correspond to the second harmonic of the engine speed near 2200 rpm.

4.1.4 Dominant Ride Frequencies

Table 4.1 summarizes the ranges of frequencies corresponding to peaks observed from the measured acceleration spectra of both machines in the transit and compaction (low-and high-density soils) modes of operation. The frequency ranges of the dominant vertical, longitudinal and pitch acceleration suggest strong coupling between these modes of vibration. The table also presents the overall frequency ranges for the peaks observed from the measured acceleration spectra. Table 4.2 further lists the frequency ranges corresponding to the peaks observed in the spectra of vibration measured during different modes of operation together with the overall frequency ranges. The results suggest that a number of frequency ranges corresponding to the vibration peaks observed during the compaction mode coincide with those observed in the transit mode, as it would be expected.

Table 4.1: Ranges of dominant ride frequencies observed from the measured acceleration spectra.

Vibration Mode	*Range of frequencies corresponding to observed peaks (Hz)*						
Vertical – seat	1.5 ~ 2.1	3.2 ~ 3.6	4.2 ~ 6.5	14.0 ~ 14.5		27.3 ~ 29.4	73.2 ~ 73.3
Vertical – cabin	1.5 ~ 2.0		4.2 ~ 7.0	14.0 ~ 14.5	18.9 ~ 19.9	27.5~ 29.4	73.3 ~ 73.4
Vertical – body	1.5 ~ 2.2		4.2 ~ 5.5	15.8 ~ 17.0		27.5 ~ 29.5	73.3 ~ 73.4
Longitudinal–cabin	1.5 ~ 1.9	2.9 ~ 3.5	4.5 ~ 5.5	12.3 ~ 14.5	18.4 ~ 19.9	27.5~ 29.5	73.3 ~ 73.4
Lateral/yaw–cabin	1.9 ~ 2.3	2.7 ~ 3.9	4.5 ~ 5.0	12.0 ~ 14.5	18.4 ~ 21.0	27.5 ~ 29.5	73.3 ~ 73.4
Lateral/yaw – body	1.9 ~ 2.3	2.7 ~ 3.9	4.5 ~ 5.0			27.5 ~ 29.5	73.3 ~ 73.4
Pitch – cabin	1.4 ~ 1.9	3.2 ~ 3.7	4.2 ~ 6.2	12.0 ~ 14.5	19.1 ~ 19.9	28.0 ~ 29.5	
Pitch – body	1.4 ~ 1.9	2.9 ~ 3.6	4.2 ~ 6.2	15.6 ~ 16.5		27.5 ~ 28.1	
Roll – cabin	1.7 ~ 2.4	2.8~ 3.9	5.7 ~ 8.0	12.0 ~ 14.5	18.4 ~ 19.9	27.5 ~ 29.5	
Roll – body	1.7 ~ 2.4	2.8~ 3.9	4.5 ~ 5.0	14.0 ~ 14.5		27.5 ~ 29.5	
Overall Range	**1.4 ~ 2.4**	**2.7~ 3.9**	**4.2 ~ 8.0**	**12.0 ~ 17.0**	**18.4 ~ 21.0**	**27.3 ~ 29.5**	**73.2 ~ 73.4**

Table 4.2: Ranges of dominant ride frequencies observed from the measured acceleration spectra during the compaction and transit tasks.

Mode	*Range of frequencies corresponding to observed peaks (Hz)*						
Transit	1.4 ~ 2.4	2.7~ 3.9	4.2 ~ 8.0	12.0 ~ 17.0	18.4 ~ 21.0		73.3 ~ 73.4
Compaction (Low density)	1.7 ~ 2.3	2.7~ 3.5	4.2 ~ 7.0	12.0 ~ 14.0	19.1 ~ 19.9	27.3 ~ 29.5	73.2 ~ 73.3
Compaction (High density)	1.4 ~ 2.4	2.7~ 3.9	4.2 ~ 8.0	12.0 ~ 17.0	19.1 ~ 19.9	27.3 ~ 29.5	73.3 ~ 73.4
Overall Range	**1.4 ~ 2.4**	**2.7~ 3.9**	**4.2 ~ 8.0**	**12.0 ~ 17.0**	**18.4 ~ 21.0**	**27.3 ~ 29.5**	**73.2 ~ 73.4**

4.2 Characterization of Vibration of Vehicles at the Worksites

The measured data acquired during the worksite runs for the 10-ton 4-cylinder and 13-ton 6-cylinder vehicles were analyzed in a similar manner to characterize the vibration transmitted to the cabin floor and the seat. The acceleration spectra obtained for different runs corresponding to each mode were generally quite comparable for each vehicle. The spectra were thus grouped together to establish the ranges of vibration along each axis, which are discussed in the following sub-sections.

4.2.1 Compaction Mode

The measured data acquired during the compaction mode were grouped together corresponding to 'low' and 'high' amplitude of the vibrator. The results obtained for the 13-ton 6-cylinder compactor, however, were limited only to the 'low' amplitude of the vibrator, since the operator opted for this setting during the test runs. Furthermore, the vibration levels measured during different passes were combined to derive the ranges, even though the magnitude of transmitted vibration generally increased in the subsequent passes. The ranges of spectra of longitudinal, lateral and vertical acceleration measured at the cabin floor of both vehicles are presented in Figs. 4.17 to 4.19, respectively, while performing compaction with 'low' vibrator amplitude. The ranges of corresponding spectra measured at the seat and the vehicle body are presented in Appendix B (Figs. B1 to B3). Figures 4.20 and 4.21 present the spectra of the pitch and roll acceleration, respectively, measured at the cabin floor of both vehicles. The magnitude of vibration and the dominant ride frequencies of the two vehicles are quite comparable to those observed from the data acquired at the test track during high-density soil compaction, although the peak roll and pitch vibration of the 10-ton 4-cylinder machine are considerably higher. It is to be noticed that the isolation mounts of this 7 years old machine might exhibit some noticeable wear.

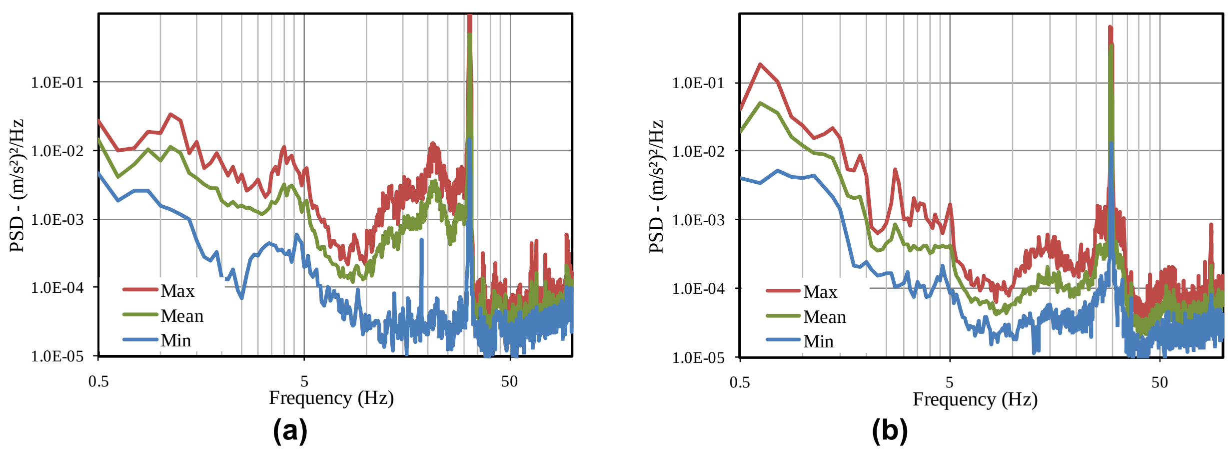
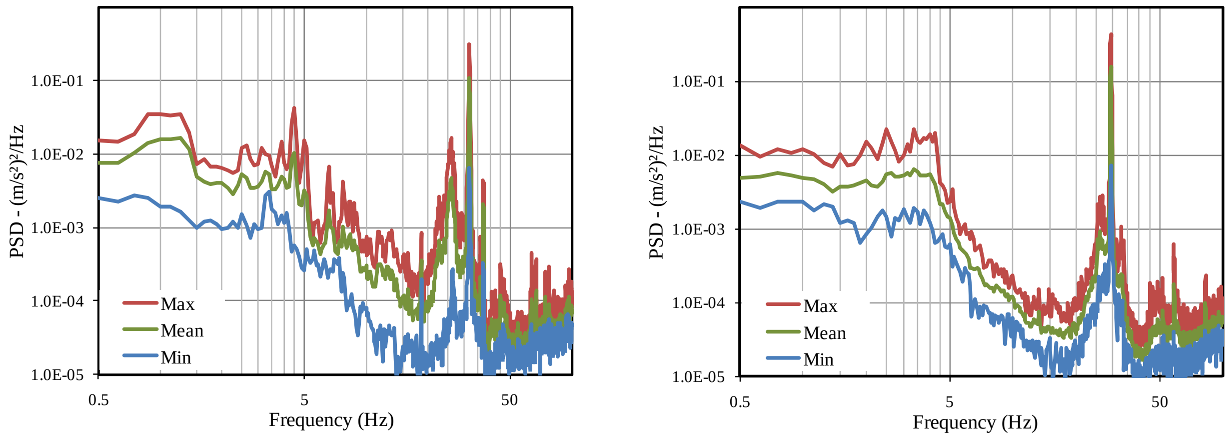


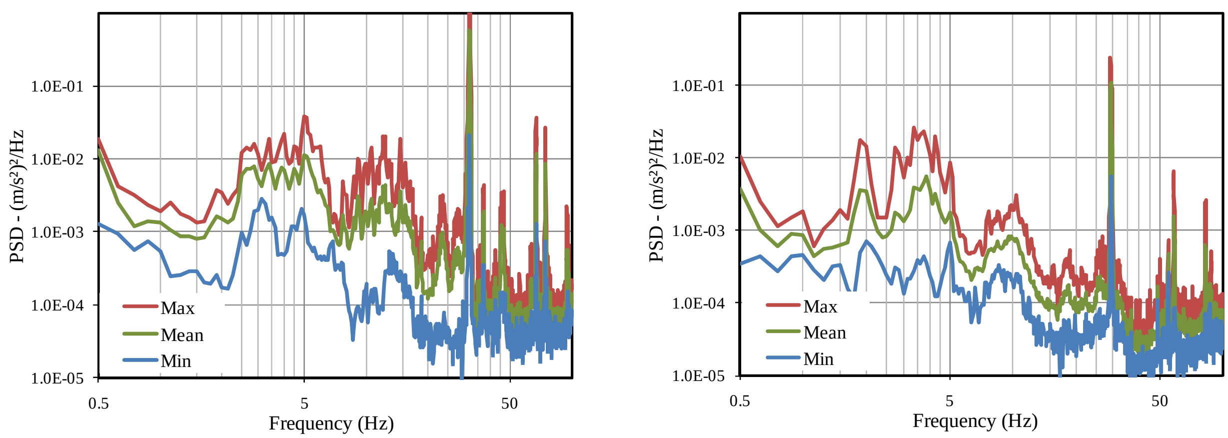
Figure 4.17: Ranges of PSD of longitudinal (x) acceleration measured at the cabin floor during compaction at low vibrator amplitude: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.

The results show relatively higher magnitude of low frequency longitudinal vibration at the seat compared to that measured at the test track (Figure 4.17), while vibration magnitudes of the cabin and the vehicle body are only slightly higher. This is attributable to considerably larger magnitudes of pitch vibration at the worksite, as seen in Figure 4.20. The magnitude of low frequency lateral vibration at the seat of the 10-ton 4-cylinder vehicle at the worksite is also higher than that at the test track, which is attributable to higher roll vibration of the cabin, as seen in Figure 4.21. In a similar manner, the magnitudes of seat as well as cabin vertical vibration of the 10-ton 4-cylinder vehicle, measured at the site, is considerably larger. The magnitude of low frequency vertical vibration at the cabin of the newer 13-ton 6-cylinder vehicle, however, is lower than that measured at the track, which is most likely due to the ‘low’ amplitude setting of the vibrator.



(a) **(b)**

Figure 4.18: Ranges of PSD of lateral (y) acceleration measured at the cabin floor during compaction at low vibrator amplitude: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.



(a) **(b)**

Figure 4.19: Ranges of PSD of vertical (z) acceleration measured at the cabin floor during compaction at low vibrator amplitude: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.

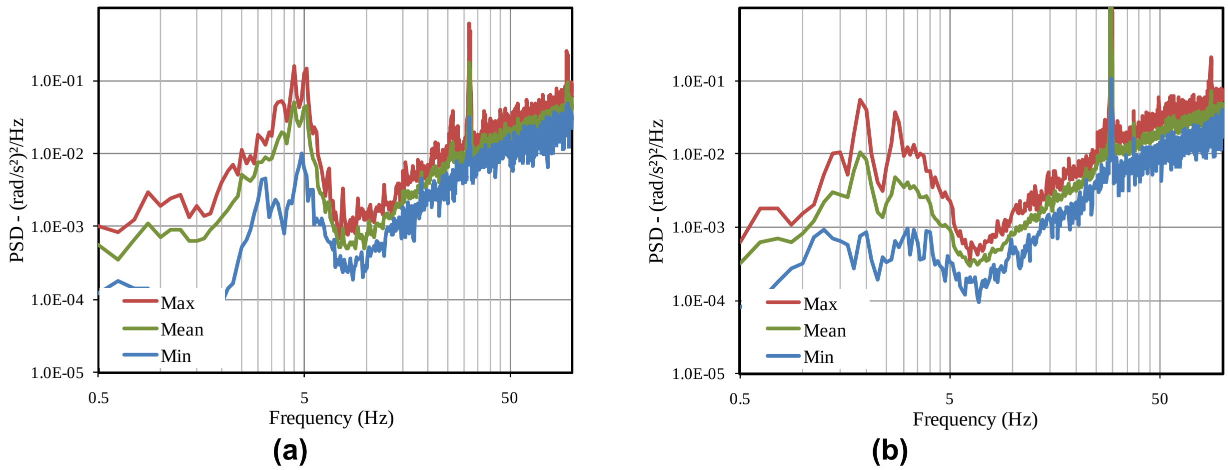


Figure 4.20: Ranges of PSD of pitch (θ) acceleration measured at the cabin floor during compaction at low vibrator amplitude: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.

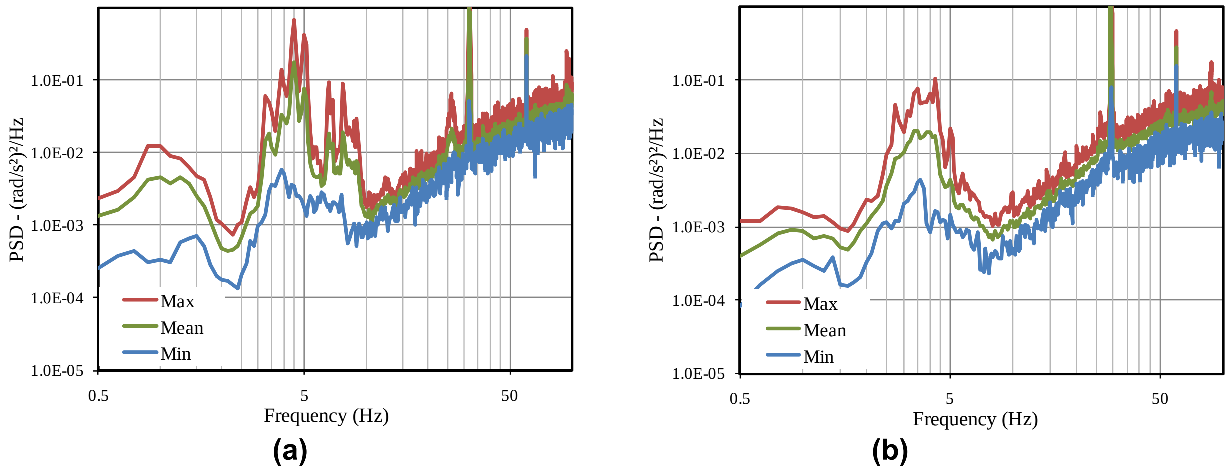


Figure 4.21: Ranges of PSD of roll (φ) acceleration measured at the cabin floor during compaction at low vibrator amplitude: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.

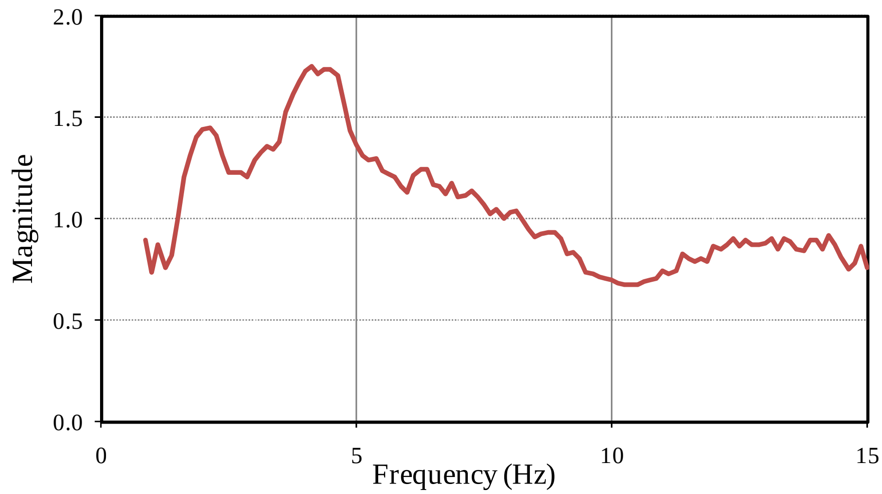


Figure 4.22: Estimated frequency response magnitude of the suspension seat employed in the13-ton 6-cylinder vehicle.

1.1 The results also show amplification of vertical vibration by the suspension seat employed in the 13-ton 6-cylinder vehicle. An estimate of the frequency response of the suspension seat was thus obtained from the mean PSD of vertical acceleration measured at the seat and the cabin floor. The frequency response magnitude, shown in Fig. 4.22, suggests that the suspension seat amplifies vertical vibration of the cabin considerably in the 4-5 Hz range. The suspension seat exhibits attenuation of vertical vibration only at frequencies above 7.5 Hz.

1.2 Soil compaction with ‘high’ amplitude setting of the vibrator does not affect the magnitude of low frequency vibration considerably but it causes a significant peak near 15 Hz (one-half of vibration frequency) due to hopping motion of the drum. This is evident from the spectra of longitudinal, lateral, vertical, roll and pitch vibration measured at the cabin floor of the 10-ton 4-cylinder compactor, as shown in Fig. 4.23. The results also show that the vertical vibration near this frequency is amplified by the cabin and the seat (Fig. B.4 in Appendix B).

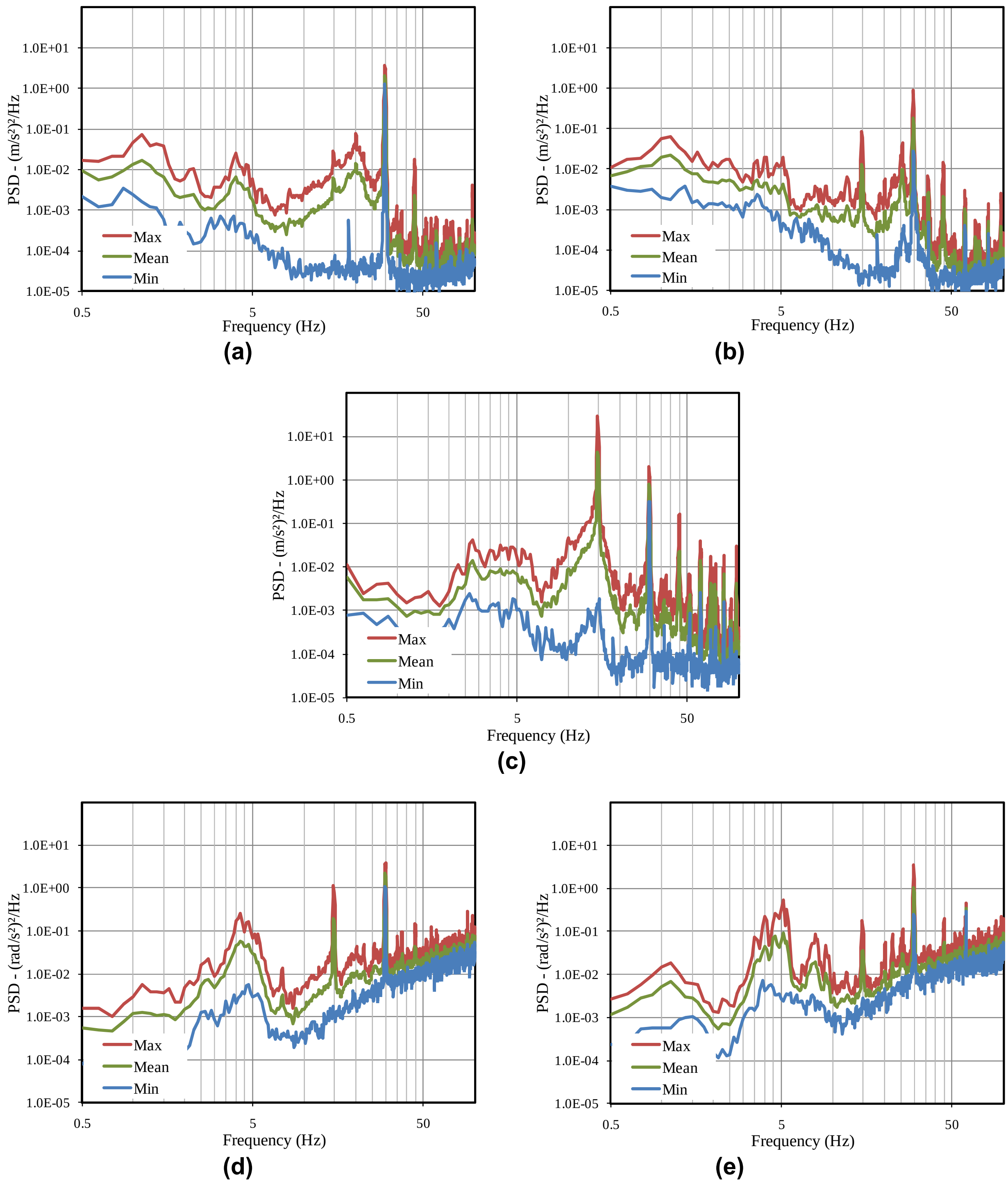
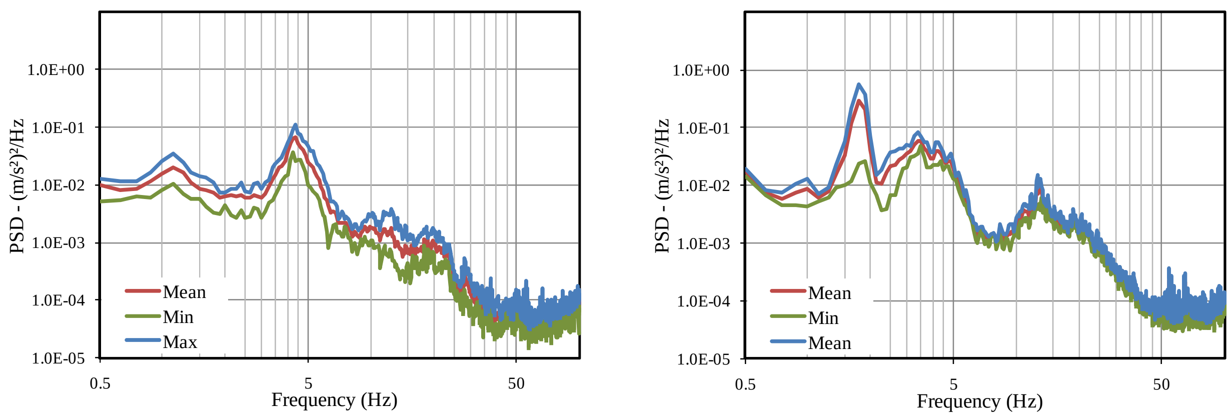


Figure 4.23: Ranges of PSD of acceleration measured at the cabin floor during high amplitude compaction of the 10-ton 4-cylinder compactor: (a) longitudinal; (b) lateral; (c) vertical; (d) pitch; and (e) roll.

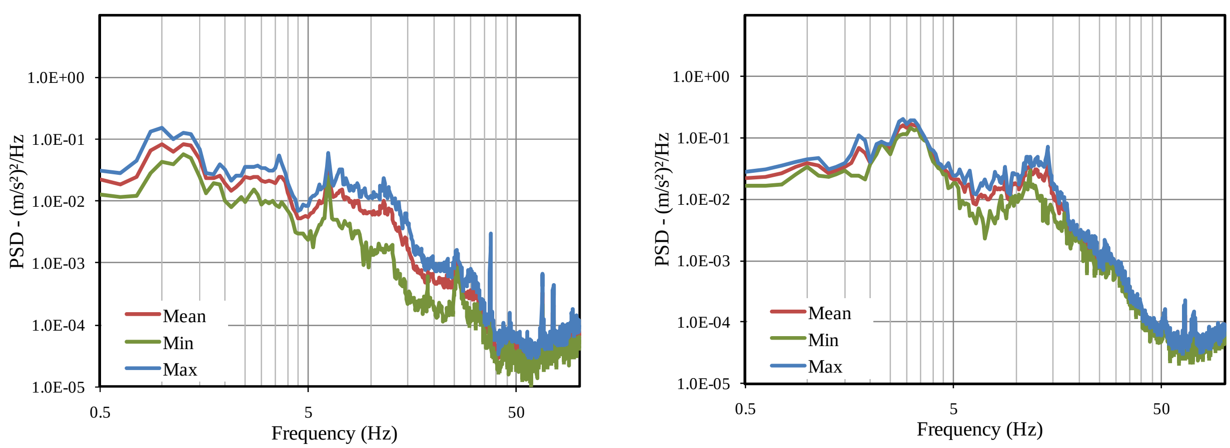
4.2.2 Transit Mode

The ranges of spectra of the longitudinal, lateral and vertical accelerations measured at the cabin floor of both vehicles in the transit mode are presented in Figs. 4.24 to 4.26, respectively. The ranges of vibration measured at the seat and body of both vehicles are presented in Appendix B (Figs. B5 to B7). The ranges of the pitch and roll vibration of the vehicle are shown in Figures 4.27 and 4.28, respectively. The ranges generally show relatively small variations, with only a few exceptions. The magnitude of low frequency vibration along all the axes is generally greater than that measured during the compaction tasks, which is attributable to higher speeds in the transit mode. Furthermore, comparisons of the spectra with those derived from the test track measurements suggest comparable dominant ride frequencies, while the magnitude of low frequency vibration is either comparable or lower than the magnitude encountered at the test track. This is mostly attributable to transit at a relatively lower average speed than that used on the test track (near 10 km/h).



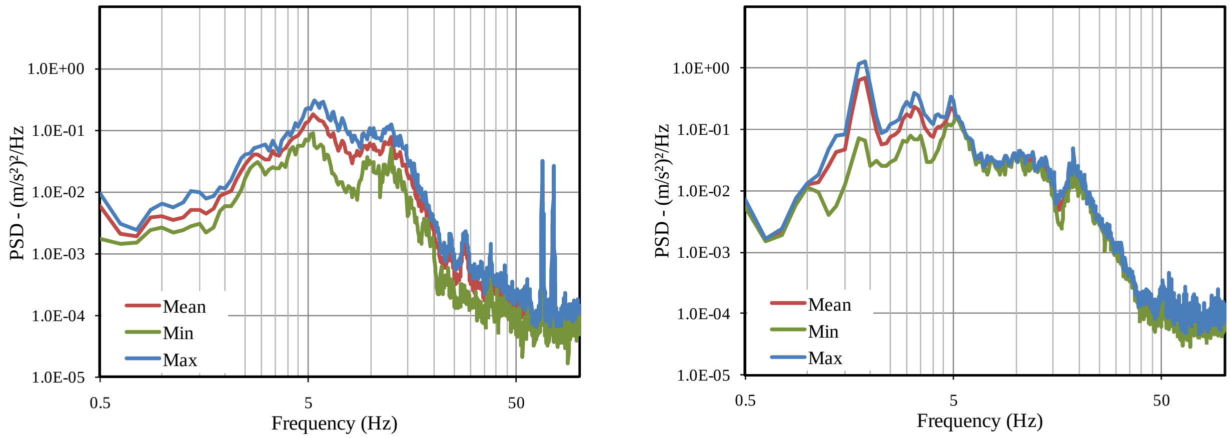
(a) **(b)**

Figure 4.24: Ranges of PSD of longitudinal (x) acceleration measured at the cabin floor in the transit mode: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.



(a) **(b)**

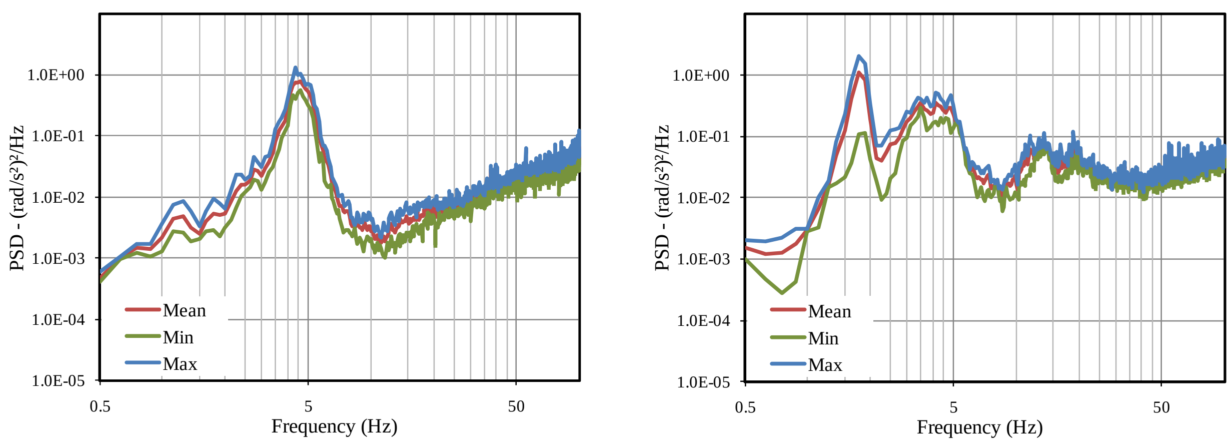
Figure 4.25: Ranges of PSD of lateral (y) acceleration measured at the cabin floor in the transit mode: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.



(a) (b)

Figure 4.26: Ranges of PSD of vertical (z) acceleration measured at the cabin floor in the transit mode: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.

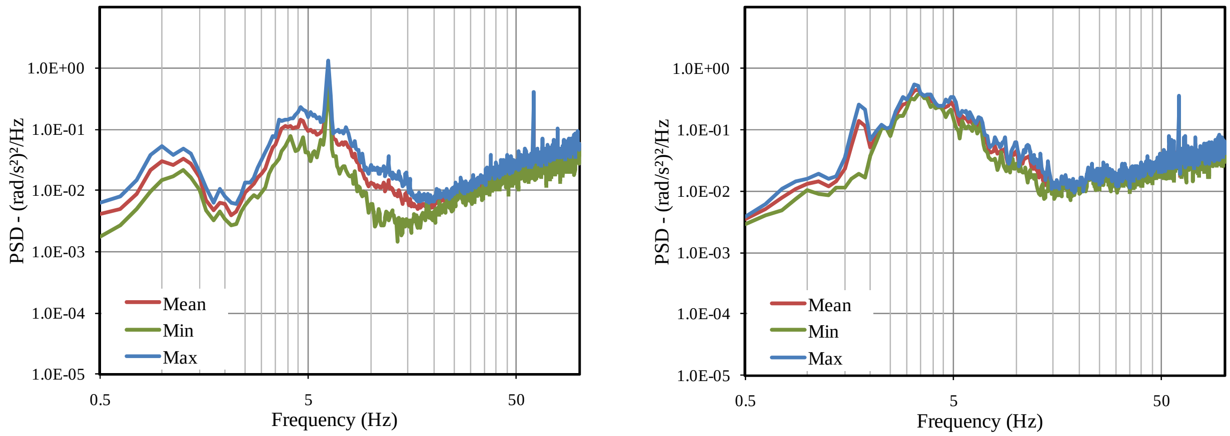
The measured acceleration spectra also show peaks at comparable frequencies in the vertical, pitch and longitudinal modes, which is suggestive of coupled pitch plane motions. Similar coupling is also evident in the roll plane as seen from the vertical, lateral and roll acceleration spectra in Figures 4.26, 4.25 and 4.28, respectively. The suspension seat employed in the 13-ton 6-cylinder vehicle yields considerably higher magnitude of vertical vibration in the 2-3 Hz range, which is evident from the comparison of the vertical acceleration spectra presented in Figs. 4.26(b) and B.7(b) in Appendix B. This suggests that the suspension seat amplifies the low frequency vertical vibration transmitted to the operator. The vertical vibration spectrum of this machine also exhibits a notable peak near 20 Hz, which is considerably attenuated by the suspension seat.



(a) (b)

Figure 4.27: Ranges of PSD of pitch (θ) acceleration measured at the cabin floor in the transit mode: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.

The ranges of acceleration spectra presented in Figures 4.17 to 4.28 define the spectral class of vibration of the vast majority of the soil compactors employed in Québec. The spectra generally exhibit dominant translational and rotational vibration in the 1-5 Hz range to which human body is known to be most sensitive in view of discomfort and potential health hazards. The exposure to such vibration is subsequently assessed using the method defined in ISO-2631-1 (1997), and the results are presented in the following section. The ranges of spectra could also be applied to explore better designs of cabin mounts, drum mounts and suspension seat to reduce the magnitude of low frequency vibration transmitted to the operators. These spectra are also vital for simulation-based design approaches in verifying vehicle models.



(a) **(b)**

Figure 4.28: Ranges of PSD of roll (φ) acceleration measured at the cabin floor in the transit mode: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.

4.3 Assessment of Vibration Exposure

The measured data acquired on the worksites under representative work conditions are further analyzed to quantify and assess the WBV exposure of the operators. For this purpose, the data acquired during different compaction and transit runs are expressed in terms of overall rms acceleration values, which are subsequently grouped together to establish the ranges of vibration in the two modes of operation. Frequency-weightings defined in ISO-2631-1(1997) are subsequently applied to determine the frequency-weighted vibration exposure along each axis corresponding to the two modes. These include the W_d-weighting for longitudinal and lateral vibration, W_k-weighting for vertical vibration and W_e-weighting for pitch and roll vibration. The international standard recommends assessment of vibration exposure on the basis of the most dominant axis of vibration. It also states that the vector sum vibration may be applied when large magnitudes of vibration are observed along multiple axes. The vector sum rms acceleration values are thus also derived and applied in accordance with the guidelines for the assessment of health risks. For this purpose an additional weighting of 1.4 is imposed on the longitudinal and lateral acceleration values.

4.3.1 Compaction Mode

Table 4.3 summarizes the means and ranges of overall rms accelerations due to vibration measured at the seat and at the operator station (cabin) of the 10-ton 4-cylinder compactor performing compaction tasks. Considering that the compactor may employ very different seats, the exposure assessments were performed on the basis of vibration measured at both the seat and the cabin floor near the operator seat. The table lists both the unweighted (***a***) and frequency-weighted ($\boldsymbol{a_w}$) rms accelerations along the x-, y- and z-axis at the seat, and along the x-, y-, z-, θ- and φ-axis of the cabin. The means and ranges of rms accelerations are also compared for the compaction performed with 'low' (6 runs) and 'high' (8 runs) vibrator amplitudes. The results clearly show that compaction with high vibrator amplitude yields substantially higher magnitude of vertical vibration, while the changes in vibration along other axes are small. The soil compaction yields predominantly high frequency vibration, which is effectively attenuated by the frequency-weightings used to compute the $\boldsymbol{a_w}$ values. The frequency-weighted values are thus considerably smaller compared to the unweighted values. The reductions in the vertical vibration values, however, are generally smaller since significant magnitude of vertical vibration occurs around 5 Hz, attributed to the pitch and vertical modes of the cabin and the vehicle body. The results suggest appreciable magnitude of frequency-weighted vertical as well as longitudinal vibration during the compaction task.

Considering that the compaction tasks invariably involve both vibrator amplitudes, the means and ranges of $\boldsymbol{a}$ and $\boldsymbol{a_w}$ are also evaluated by combining the data for both amplitudes, which are also presented in Table 4.3. The results show extreme variations in the vertical vibration values; the frequency-weighted values vary from a low of 0.27 m/s^2 to an extreme of 2.88 m/s^2. These are attributable to many factors such as variations in the soil density, the ratio of vibrator start-up/stoppage time over the duration of a pass, and possible variations in speed. The results further show that the rms values due to seat vibration are considerably higher than those due to the cabin vibration, irrespective of the vibrator amplitude. The mean frequency-weighted longitudinal acceleration at the seat is nearly 3 times that at the cabin, which is partly attributed to high pitch mode vibration and high location of the seat. The vertical vibration value at the seat is nearly 30% higher than that at the cabin floor. These results suggest that the operator seat amplifies the vertical vibration considerably. A comparison of the vertical acceleration spectra measured at the vehicle body (Fig. B.7) with that measured at the cabin floor (Fig. 4.26) also shows amplification of vertical vibration by the cabin mounts.

The vibration total values of the weighted rms accelerations (a_{we}) are also computed using the method defined in ISO-2631-1(1997):

$$\mathrm{a}_{\mathrm{we}} = \sqrt{(k_x a_{wx})^2 + (k_y a_{wy})^2 + (k_z a_{wz})^2} \qquad (4.1)$$

where a_{wx}, a_{wy} and a_{wz} are frequency-weighted rms accelerations due to vibration along x-, y- and z-axis, respectively, and k_x=1.4, k_y=1.4 and k_z=1.0 are multiplying factors. Comparisons of the vibration total values with the individual axis values suggest that the vibration transmitted to the operator during the high-amplitude compaction task is predominant along the vertical axis, while the longitudinal vibration is also important under low-amplitude compaction.

The means and ranges of overall rms accelerations due to vibration measured at the seat and the operator station (cabin) of the 13-ton 6-cylinder during the compaction task are summarized in Table 4.4. The results are presented for the low amplitude compaction alone, since the operator opted for this setting in all of the 13 compaction runs. The table presents the means and ranges of both unweighted and frequency-weighted rms accelerations along each axis together with the total vibration values. The results show substantially lower levels of vibration of this vehicle compared to the 10-ton 4-cylinder compactor, particularly along the vertical axis. This is attributed to a number of factors, namely: the compaction in this case was performed with ‘low’ amplitude setting; the 13-ton 6-cylinder compactor was a new vehicle, while the 10-ton 4-cylinder unit was approximately 7 years old (representing the average compactors in use in Québec); and the operator cabin of the 13-ton 6-cylinder compactor was supplied by the manufacturer with appropriately tuned cabin mounts.

Table 4.3: The means and ranges of overall frequency-weighted and unweighted rms acceleration values (m/s^2 or rad/s^2) due to vibration measured at the seat and the cabin of the 10-ton 4-cylinder compactor performing soil compaction with low and high amplitudes of the vibrator.

Axis	Low-amplitude compaction				High-amplitude compaction				Overall	
	a		a_w		*a*		a_w		a_w	
	range	**mean**	range	**mean**	range	**mean**	range	**mean**	range	**mean**
Seat -x	1.52-1.59	**1.55**	0.28-0.38	**0.32**	1.87-2.23	**2.02**	0.29-0.45	**0.35**	0.28-0.45	**0.34**
Seat -y	0.41-0.49	**0.45**	0.13-0.24	**0.19**	0.45-0.72	**0.50**	0.12-0.18	**0.15**	0.12-0.24	**0.16**
Seat -z	0.53-1.02	**0.80**	0.27-0.60	**0.45**	0.66-3.77	**1.27**	0.39-2.88	**0.91**	0.27-2.88	**0.66**
Seat - a_{we}			0.51-0.87	**0.69**			0.59-2.96	**1.06**	0.51-2.97	**0.84**
Cabin -x	0.57-0.65	**0.59**	0.06-0.16	**0.10**	1.01-1.14	**1.07**	0.09-0.20	**0.12**	0.06-0.20	**0.11**
Cabin -y	0.22-0.40	**0.30**	0.07-0.17	**0.13**	0.24-0.82	**0.39**	0.09-0.20	**0.13**	0.07-0.20	**0.13**
Cabin -z	0.65-0.72	**0.66**	0.27-0.40	**0.30**	0.62-3.21	**1.10**	0.27-2.41	**0.73**	0.27-2.41	**0.51**
Cabin -θ	1.25-1.32	**1.29**	0.04-0.09	**0.07**	1.58-2.12	**1.74**	0.06-0.14	**0.08**	0.04-0.14	**0.08**
Cabin -φ	1.55-1.61	**1.58**	0.07-0.13	**0.09**	1.50-2.19	**1.64**	0.07-0.13	**0.09**	0.07-0.13	**0.09**
Cabin - a_{we}			0.30-0.52	**0.38**			0.32-2.44	**0.78**	0.29-2.44	**0.56**

Table 4.4: The means and ranges of overall frequency-weighted and unweighted rms acceleration values (m/s^2 or rad/s^2) due to vibration measured at the seat and the cabin of the 13-ton 6-cylinder compactor performing soil compaction with low amplitude of the vibrator.

Axis	Low-amplitude compaction			
	a		a_w	
	range	**mean**	range	**mean**
Seat -x	0.36-0.46	**0.41**	0.09-0.23	**0.15**
Seat -y	0.42-0.75	**0.55**	0.15-0.31	**0.19**
Seat -z	0.14-0.22	**0.18**	0.09-0.18	**0.14**
Seat - a_{we}			0.26-0.57	**0.37**
Cabin -x	0.39-0.44	**0.41**	0.06-0.20	**0.12**
Cabin -y	0.25-0.37	**0.30**	0.08-0.15	**0.10**
Cabin -z	0.24-0.29	**0.25**	0.12-0.16	**0.13**
Cabin -θ	1.40-1.66	**1.53**	0.05-0.09	**0.06**
Cabin -φ	1.49-1.64	**1.57**	0.06-0.08	**0.07**
Cabin - a_{we}			0.18-0.39	**0.26**

Although the 13-ton 6-cylinder compactor was equipped with a suspension seat, the results suggest that the suspension seat amplifies the cabin vertical vibration slightly. The a_{wz} value at the operator seat is approximately 8% higher than that at the cabin floor. The magnitudes of the longitudinal and lateral vibration at the seat, however, are considerably larger than that at the cabin floor, which is attributable to contributions of the pitch and roll vibration of the vehicle, respectively, together with the high seat location. From the results, it can be concluded that the magnitude of vibration of the relatively new 13-ton 6-cylinder machine during compaction is quite small and the operator exposure to such vibration would be of minimal concern. The magnitude of vibration of the 10-ton 4-cylinder compactor in the compaction mode, however, is quite large.

4.3.2 Transit Mode

The means and ranges of unweighted and weighted rms acceleration values of vibration measured in the transit mode are evaluated in a similar manner. These are evaluated at the seat and cabin along each individual axis and summarized in Table 4.5 for both compactors. The results clearly show that the vibration transmitted in the travel mode differs considerably from the vibration transmitted in the compaction mode. For the 10-ton 4-cylinder machine, the unweighted values in the transit mode are generally lower than those in the compaction mode due to the presence of dominant high frequency components during compaction. The weighted values in the travel mode, however, are considerably greater than those in the compaction mode. This is attributed to large magnitude of low frequency vibration and the absence of vibrator-induced frequency components. The unweighted rms vibration values of the 13-ton 6-cylinder machine, however, are considerably higher than those in compaction, as seen from the results summarized in tables 4.4 and 4.5. This is, in-part, attributed to low vibrator amplitude used during compaction. The results further show that the newer 13-ton 6-cylinder machine yields considerably higher levels of frequency-weighted cabin vibration than the 10-ton 4-cylinder machine in all the axes, except for the vertical mode. This suggests that the cabin mounts in the 13-ton 6-cylinder machine provide effective attenuation of vertical vibration only, while the greater roll and pitch vibration of the vehicle yields higher magnitudes of longitudinal and lateral vibration.

Table 4.5: The means and ranges of overall frequency-weighted and unweighted rms acceleration values (m/s^2 or rad/s^2) due to vibration measured at the seat and the cabin of the 10-ton 4-cylinder and 13-ton 6-cylinder compactors during transit.

Axis	10-ton 4-cylinder Compactor				13-ton 6-cylinder Compactor			
	a		a_w		a		a_w	
	range	**mean**	range	**mean**	range	**mean**	range	**mean**
Seat -x	0.74-1.32	**0.97**	0.42-0.71	**0.54**	0.61-1.04	**0.80**	0.31-0.79	**0.54**
Seat -y	0.38-0.53	**0.45**	0.13-0.19	**0.16**	0.81-0.85	**0.83**	0.45-0.46	**0.45**
Seat -z	1.06-1.88	**1.43**	0.99-1.81	**1.35**	0.93-1.56	**1.20**	0.85-1.18	**0.99**
Seat - a_{we}			1.17-2.08	**1.57**			1.14-1.74	**1.39**
Cabin -x	0.26-0.42	**0.36**	0.14-0.23	**0.20**	0.37-0.60	**0.47**	0.20-0.44	**0.31**
Cabin -y	0.33-0.54	**0.45**	0.23-0.36	**0.30**	0.66-0.80	**0.72**	0.40-0.41	**0.41**
Cabin -z	0.66-1.16	**0.90**	0.60-1.13	**0.85**	0.82-1.23	**1.00**	0.74-0.99	**0.85**
Cabin -θ	1.48-1.71	**1.60**	0.19-0.27	**0.23**	1.62-2.08	**1.83**	0.23-0.52	**0.37**
Cabin -φ	1.51-1.64	**1.57**	0.15-0.22	**0.20**	1.83-1.85	**1.83**	0.30-0.33	**0.31**
Cabin - a_{we}			0.71-1.28	**0.99**			0.97-1.30	**1.11**

The results further show that the cabin vertical vibration is amplified by the seat in both vehicles. While the suspension seat in the 13-ton 6-cylinder unit amplifies vertical vibration by nearly 16%, the vibration amplification by the cushioned seat in the 10-ton 4-cylinder machine is in the order of 60%. It can thus be concluded that an appropriately tuned suspension seat would be beneficial in reducing the exposure to low frequency vertical vibration. Considering that vertical vibration mostly predominates around 5 Hz, an adequately damped suspension seat, with a natural frequency in the order of 1.5 Hz, would yield more effective attenuation of the vertical vibration, given an adequate adjustment to the operators' weight.

4.3.3 Equivalent Daily Vibration Exposure

Table 4.5 also presents the ranges and means of the total vibration values for both machines in the travel mode. The cabin vibration is dominant along the vertical axis for both machines. The assessment of exposure in the travel mode could thus be carried out on the basis of the vertical vibration magnitude alone. The magnitudes of frequency-weighted longitudinal vibration at the seat, however, are approximately 40% and 50% of the vertical vibration for the 10-ton and 13-ton machines, respectively. This may require consideration of the vector sum vibration. The ISO-2631-1 (1997) standard requires that the assessment of the effect of vibration on health shall be made independently along each axis and that the assessment be made with respect to the highest frequency-weighted acceleration determined in any axis on the seat pan. It further requires that the frequency-weighted values be applied together with the multiplying factors defined in section 4.3.1, while the vibration total value, defined in Eq. (4.1), could be applied if a single dominant axis cannot be identified.

The results in Tables 4.3 to 4.5 clearly show substantially different levels of weighted vibration along the three axes for both compaction and travel modes. Moreover, the daily operator exposure comprises vibration during both modes. The daily vibration exposure is thus determined by considering combinations of compaction and transit vibration exposure. This would however requires average patterns of the operator work routines involving the daily durations of compaction and transit modes, and other activities performed in a no-vibration environment. Following a few consultations with the operators, the exposure assessments are performed for three different average work patterns:

- 6 hours compaction coupled with 1 hour transit and 1 hour of other activities performed in a vibration free environment;
- 6.25 hours compaction coupled with 0.75 hour transit and 1 hour of other activities performed in a vibration free environment; and
- 6.5 hours compaction coupled with 0.50 hour transit and 1 hour of other activities performed in a vibration free environment.

The eight-hour equivalent exposure values, also denoted as daily vibration exposure, A(8), are subsequently computed from the frequency-weighted vibration values derived for the compaction and the transit modes for each of the above exposure patterns, in the following manner:

$$A(8) = \sqrt{\frac{\left(a_{we}^2\right)_{com} T_{com} + \left(a_{we}^2\right)_{tran} T_{tran}}{8}} \qquad (4.2)$$

where a_{we} is the equivalent exposure value in a given mode, T is the exposure duration for the particular mode, and the subscripts 'com' and 'tran' denote the compaction and transit modes of operation. The equivalent exposure is equal to the frequency-weighted rms acceleration along a given axis when predominant vibration is observed along a single axis, as in the case of the travel mode (Table 4.5; vertical axis) for both vehicles. The a_{we} equals the total vibration value computed using Eq. (4.1) when the vibration levels along the three translational axes are comparable, as in the case of the 13-ton 6-cylinder machine during compaction. However, the a_{we} value for the 10-ton machine in the compaction mode is taken as the vertical frequency-weighted acceleration (Table 4.3), since the vibration level along the vertical axis is predominant.

The equivalent exposure values are computed using both the seat and cabin vibration for both vehicles. The equivalent values are taken as those of the vertical vibration except for the compaction mode vibration of the 13-ton 6-cylinder machine. The equivalent exposure values are computed using the ranges and mean values of rms accelerations during the transit and compaction modes and summarized in Table 4.6. It must be noted that the operator exposure to the upper limits of the vibration values (presented in Tables 4.3 to 4.5) would occur over a very short duration, since such vibration levels could be encountered only during final passes of compaction or during vehicle interactions with highly rough surfaces. The results are thus discussed using only the mean A(8) values presented in Table 4.6. The results show that the mean A(8) values for the 10-ton 4-cylinder machine exceed the daily exposure action value of 0.5 m/s^2 recommended in the EC Directive (above that value, employers are required to control the WBV risks), but are well below the daily exposure limit value of 1.15 m/s^2 (exposure limit value above which workers must not be exposed) for all the three exposure patterns considered. The directive suggests that appropriate actions must be taken to reduce vibration through the use of supplementary equipment or alternative work procedures, when exposure level exceeds the action limit value (EN 2002/44/EC, 2002). The results also show that the exposure values corresponding to the cabin vibration are only slightly above the action value for all three patterns, while the values corresponding to the seat vibration are in the order of 0.7 m/s^2. These results suggest that the use of an adequately tuned suspension seat would be vital for limiting the exposure close to the action value. Further efforts in identifying optimal cab mounts would also be highly desirable.

Table 4.6: The range and mean values of eight-hour equivalent exposure, A(8) in m/s^2, due to vibration measured at the seat and cabin of the 10-ton 4-cylinder and 13-ton 6-cylinder compactors considering different daily distributions of compaction and transit tasks.

		Range (**mean**) of A(8), m/s^2		
Duration (hours)	Compaction, T_{com}	6.0	6.25	6.5
	Transit, T_{tran}	1.0	0.75	0.5
10-ton 4-cyl.; seat		0.42-2.58 (**0.74**)	0.39-2.61 (**0.71**)	0.35-2.64 (**0.68**)
13-ton 6-cyl.; seat		0.38-0.65 (**0.48**)	0.35-0.62 (**0.45**)	0.32-0.69(**0.41**)
10-ton 4-cyl.; cab		0.32-2.13 (**0.53**)	0.30-2.17 (**0.52**)	0.29-2.20 (**0.51**)
13-ton 6-cyl.; cab		0.31-0.48 (**0.37**)	0.28-0.46 (**0.34**)	0.25-0.43 (**0.31**)

The mean daily exposure values for the 13-ton 6-cylinder machine, based on the cab vibration, are considerably lower than the action value, while those based on the seat vibration approach 0.48 m/s^2. It needs to be emphasized that the exposure values derived for this machine are applicable only for the 'low' amplitude setting of the vibrator. Compaction with the 'high' amplitude setting may cause the exposure values to approach or exceed the action value. The results for this machine also show amplification of vibration by the suspension seat. It is thus suggested to re-examine the seat-suspension properties in light of the ranges of vibration spectra established in this study and/or ensure adequate adjustment of the seat to the operators' weight.

5. CONCLUSIONS AND RECOMMENDATIONS

The vibration properties of selected compactors were measured on a test track under controlled conditions and at worksites under typical work conditions. The selected vehicles included three 10-ton machines, which represent the vast majority of the compactors used in Québec, and a newer 13-ton machine. The measurements were performed in the compaction and transit modes. The results of the study suggest that soil compactors transmit high levels low frequency whole-body vibration in the transit mode, while the magnitudes of such vibration are low in the compaction mode. The spectra of vehicle vibration in the compaction mode revealed a distinct high magnitude peak corresponding to the eccentric vibrator speed, near 30 Hz, irrespective of the location and direction of the measured vibration, and of the machine. The magnitude of vehicles' vibration increased during compaction of higher density soils due to greater interactions of the drum and the tires with soils of higher stiffness, and with 'high' vibrator amplitude setting. The measured data also showed considerable hopping of the drum and higher transmitted vibration, particularly near 15 Hz (one-half of the vibrator frequency).

The magnitude of low frequency vibration was considerably higher in the transit mode along all the axes, while the high frequency components attributed to the vibrator (turned off in transit) were not evident. The dominant translational and rotational vibration in the transit mode generally occurred in the 1-6 Hz frequency range, a range to which human body is known to be more sensitive in view of discomfort and potential health hazards (ISO-2631-1). These were attributed to the vertical and pitch modes of the vehicles and the cabin. The most dominant cabin vibration occurred in the 4-6 Hz range along the vertical axis, which was amplified by the cushion seats that are used in the vast majority of compactors in Québec. The suspension seat employed in the newer 13-ton machine also showed amplification of vibration at low frequencies. Furthermore, the cabin mounts provided attenuation of only high frequency vibration, while the large pitch and roll motions of the vehicles caused greater magnitudes for the longitudinal and lateral vibration at the operator seat.

The magnitude of low frequency vibration of the vehicles at the worksites was generally lower than those measured on the test track for the 10-ton machines. This was mostly attributable to relatively lower transit speed (selected by the operator) at the worksites than that used on the test track (near 10 km/h). The magnitude of the low frequency vibrations of the 13-ton machine in the transit mode was either comparable or higher than that of the 10-ton machine. The spectra generally revealed amplification of vibration by the cabin mounts and the seat. The spectra of vibration acquired during different repeated runs were combined to define the ranges of vibration spectra, which could be applied to explore better designs of operator station mounts, drum mounts and suspension seat to reduce the transmission of low frequency vibration.

These spectra would also be applicable for simulation-based design approaches in verifying different vehicle models. The vertical cabin vibration of the 10-ton machine was amplified by nearly 60% at the seat, compared to an amplification of only 16% for the suspension seat used in the 13-ton compactor. The assessment of vibration data in accordance with ISO-2631-1 and EC Directive revealed considerably higher exposure values for the 10-ton machine in the compaction mode compared to the 13-ton machine. The daily exposure values, A(8), for the two machines were dependent upon the daily durations of the compaction and transit tasks in addition to other activities performed in a vibration-free environment. These were computed by considering three different work patterns involving 6, 6.25 and 6.5 hours of compaction and 1, 0.75 and 0.5 hours of transit, respectively, together with 1 hour of other activities performed in a vibration-free environment.

From the results, it was concluded that the mean A(8) values based on seat vibration of the 10-ton machine exceed the EC recommended action value of 0.5 m/s^2 but remained below the exposure limit of 1.15 m/s^2, irrespective of the work pattern considered. The exposure values corresponding to the cabin vibration were also slightly above the action value. The mean A(8) value for the 13-ton machine based on the cabin vibration was considerably lower than 0.5 m/s^2, but the mean value based on the seat vibration approached 0.47 m/s^2. It is anticipated that the A(8) values for this machine would be higher when compaction is performed with a 'high' amplitude setting of the vibrator. It needs to be emphasized that the vibration levels observed in this study are limited to selected vehicles and operating conditions, although the selected vehicles represent the most common ones employed in Québec. The exposure levels, however, would differ for different compactor models and operating conditions.

The results suggest that the seat and the cabin mounts amplify the low frequency vibration for all the vehicles considered in the study but this amplification is limited for the 13-ton compactor equipped with more sophisticated cab mounts. Furthermore, the dominant vibration in both compaction and travel modes occurred along the vertical axis, particularly for the 10-ton compactors that represent the largest proportion of such vehicles used in Québec. The transmission of vertical vibration to the operator could be greatly reduced through design and implementation of an adequately tuned suspension seat. The results attained from a preliminary simulation study revealed that a suspension seat could yield a nearly 60% reduction in the vertical vibration (Kordestani, 2010). It is thus strongly recommended to employ suspension seats with adequate damping and natural frequency in the order of 1.5 Hz. It is also recommended to examine the design of suspension seats used in the newer 13-ton vehicles and/or their adequate adjustment to the operators' weight, in order to limit their vibration amplification. Further efforts are also desirable in identifying optimal cabin mounts for limiting WBV exposure along the translational and rotational axes. Analytical and simulation methods need to be developed to explore alternate designs of cabin and drum mounts for limiting the vibration exposure while preserving the compaction efficiency of the vehicle.

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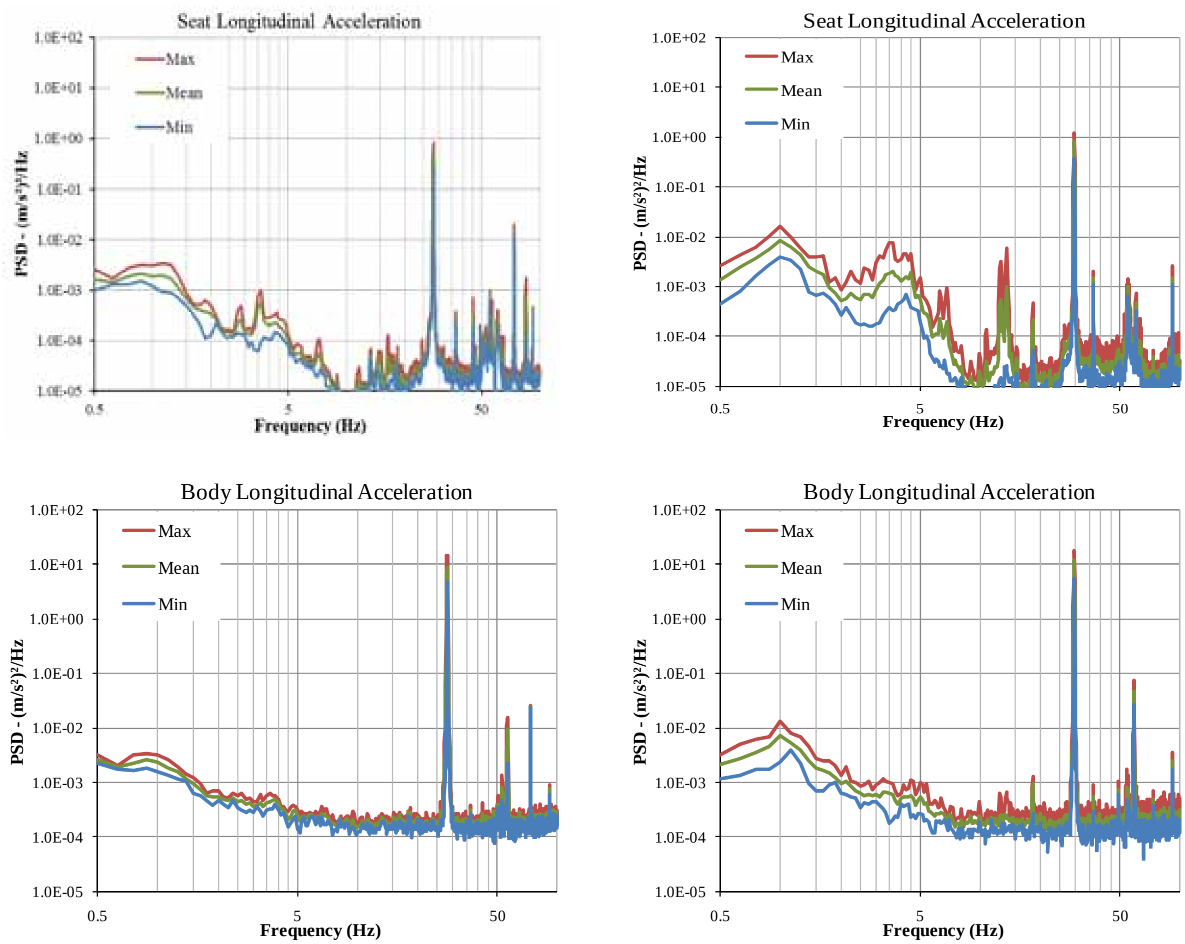
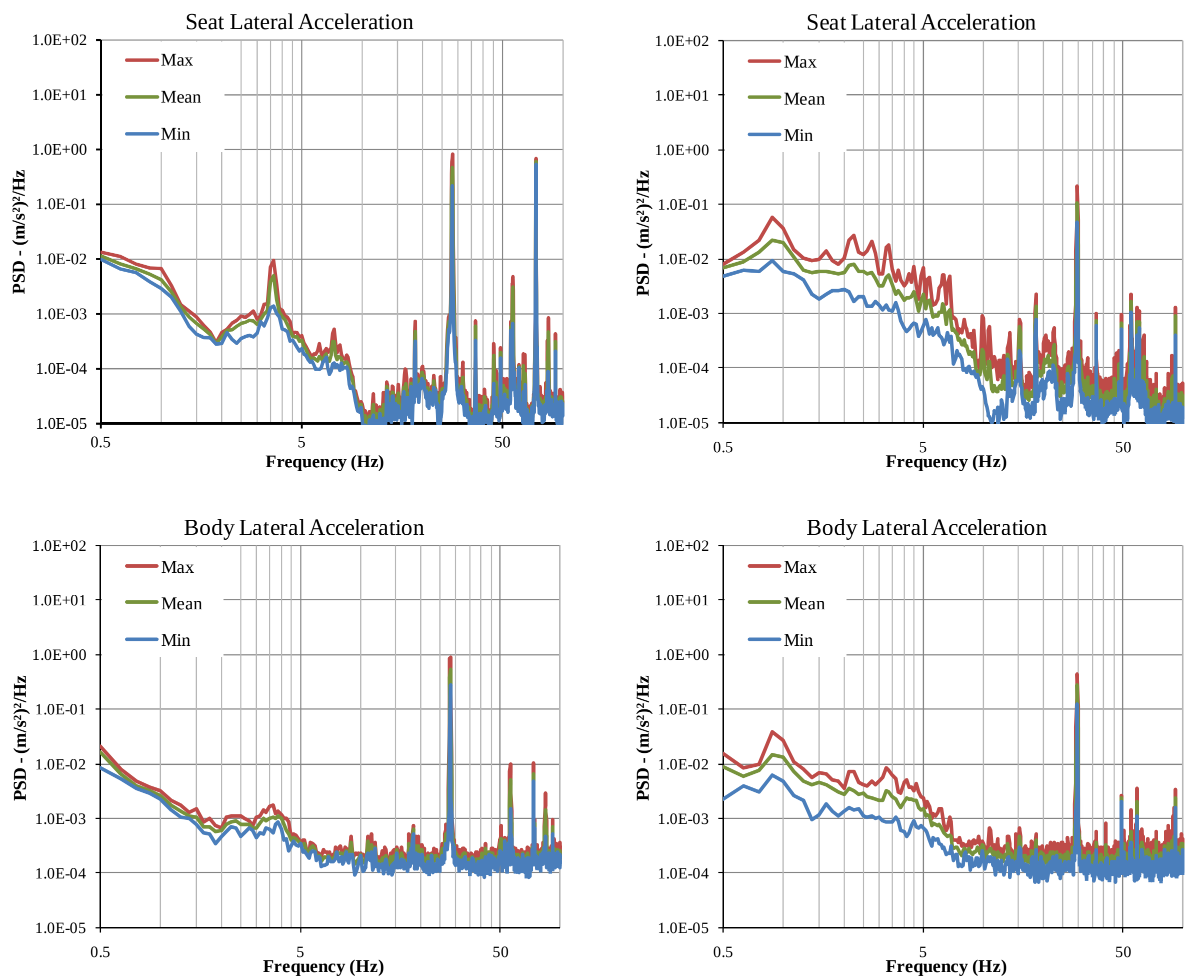
APPENDIX A

RANGES OF SPECTRA OF VIBRATION MEASURED DURING LOW- AND HIGH-DENSITY SOIL COMPACTION



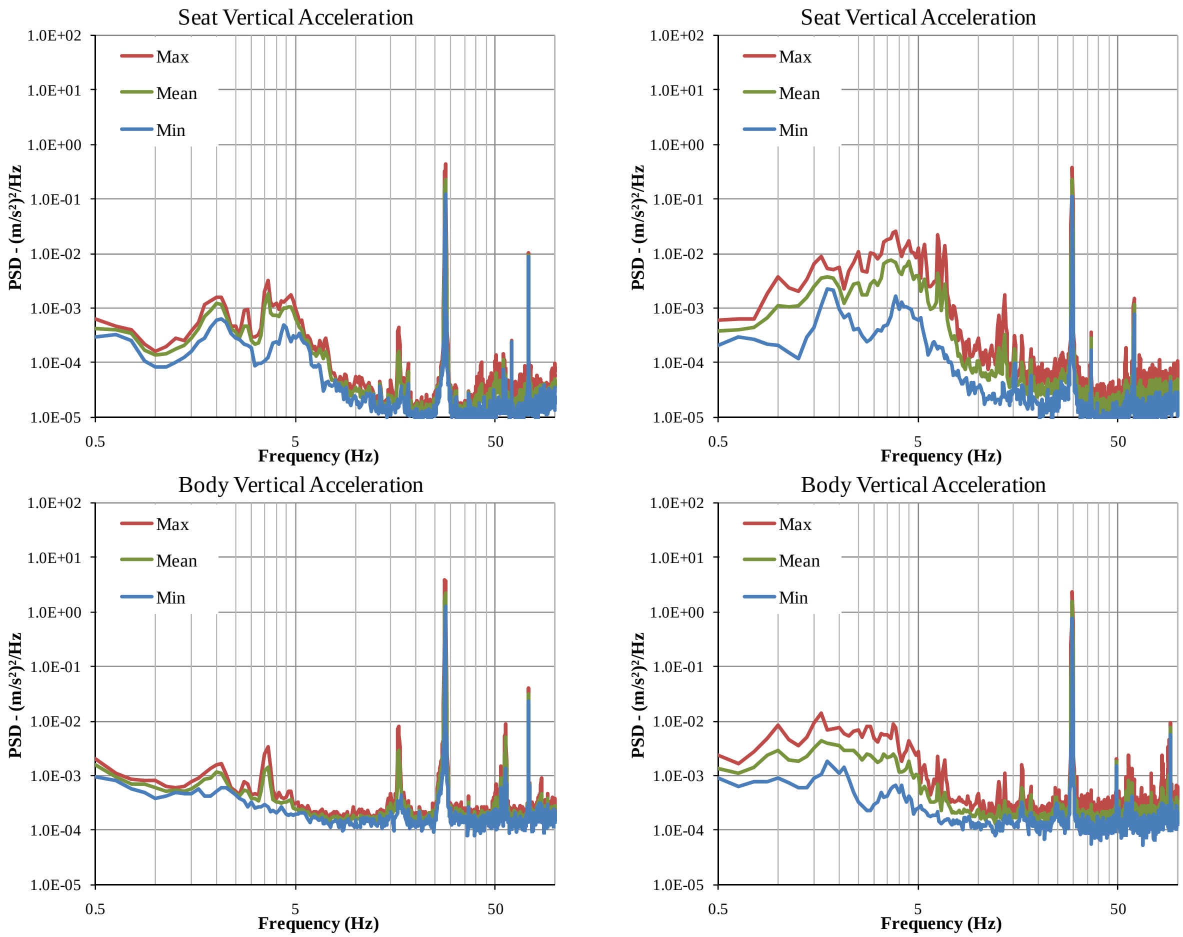
(a) **(b)**

Figure A.1: Ranges of PSD of longitudinal (x) acceleration measured at the seat and vehicle body during low-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



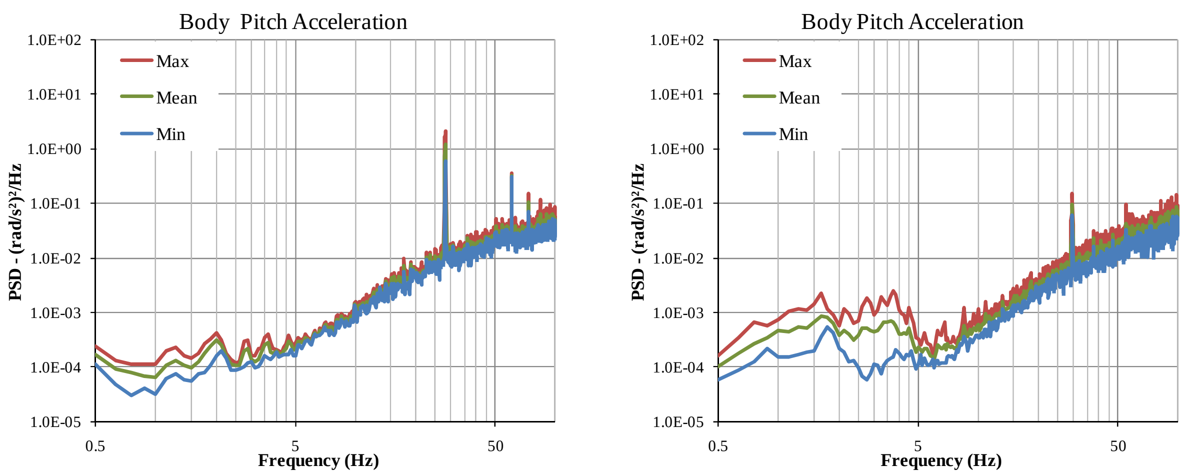
(a) **(b)**

Figure A.2: Ranges of PSD of lateral (y) acceleration measured at the seat and vehicle body during low-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



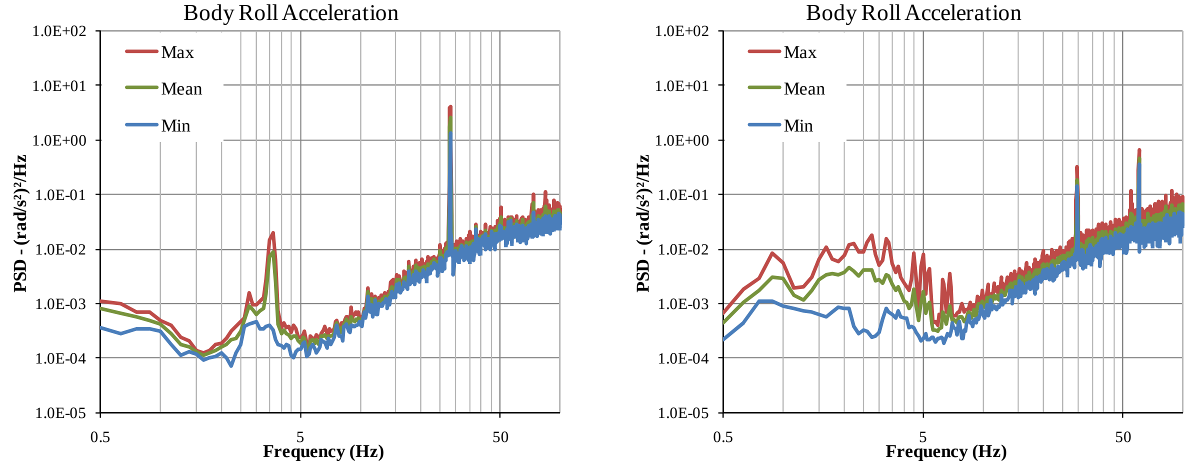
(a) **(b)**

Figure A.3: Ranges of PSD of vertical (z) acceleration measured at the seat and vehicle body during low-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



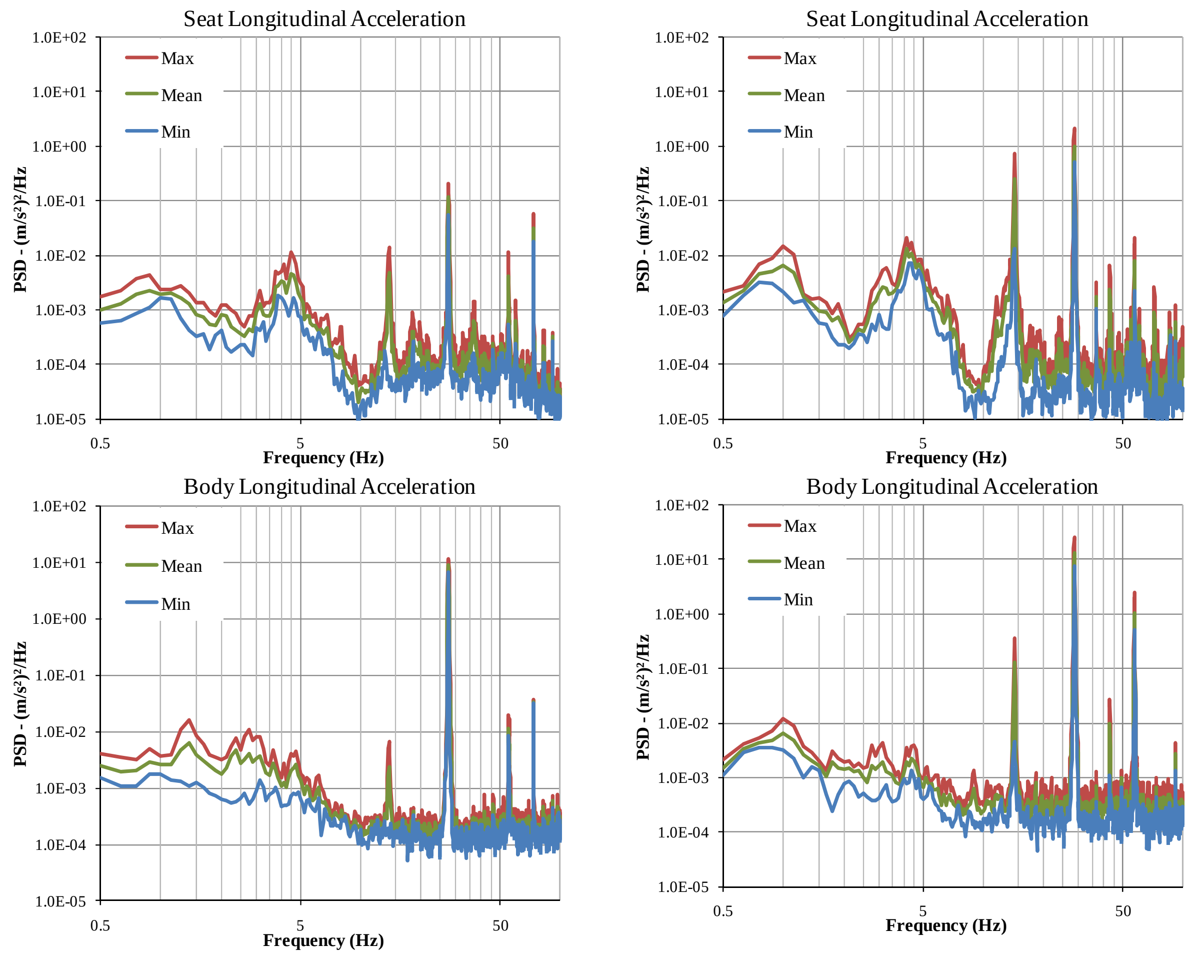
(a) **(b)**

Figure A.4: Ranges of PSD of pitch (θ) acceleration measured at the vehicle body during low-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



(a) **(b)**

Figure A.5: Ranges of PSD of roll (φ) acceleration measured at the body during low-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



(a) **(b)**

Figure A.6: Ranges of PSD of longitudinal (x) acceleration measured at the seat and vehicle body during high-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.

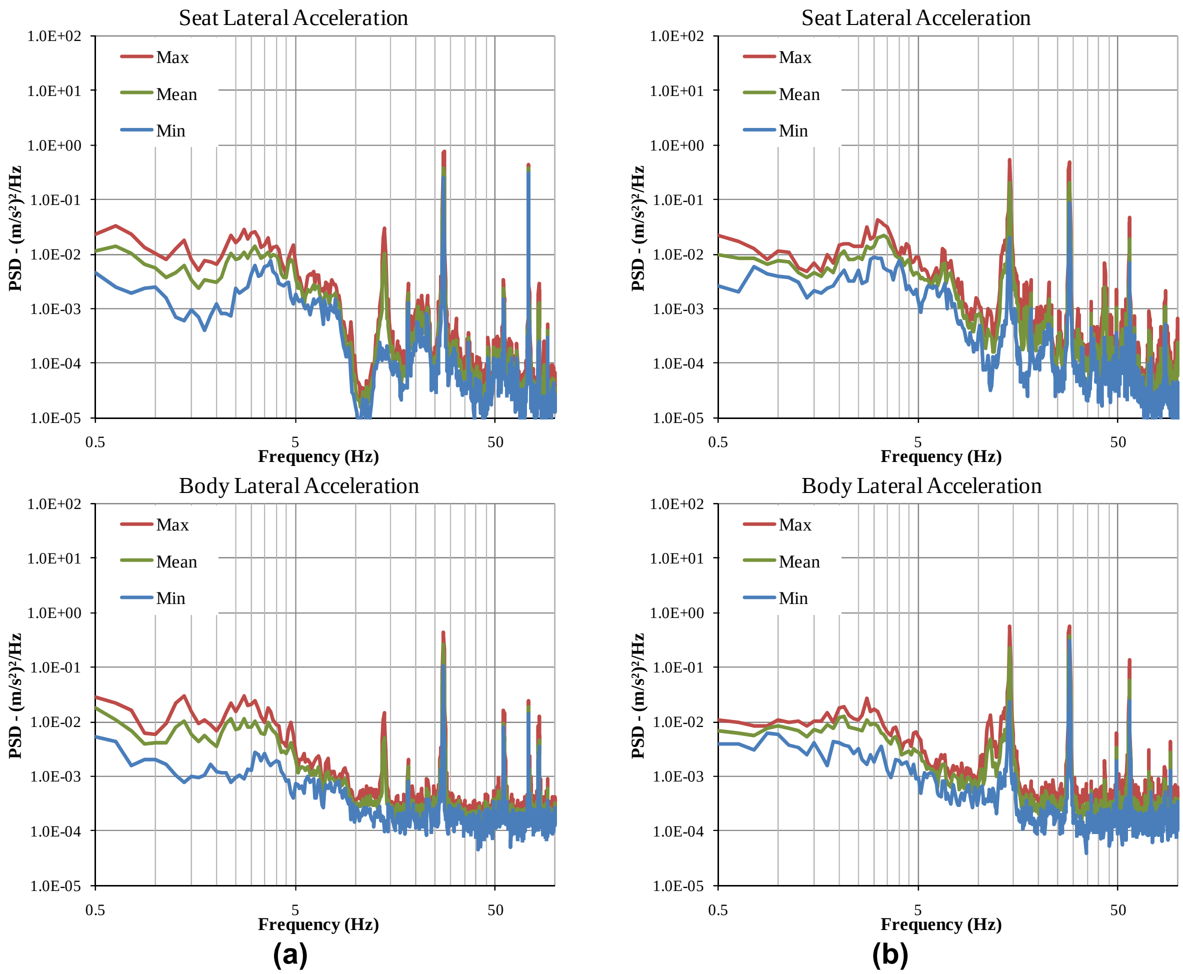
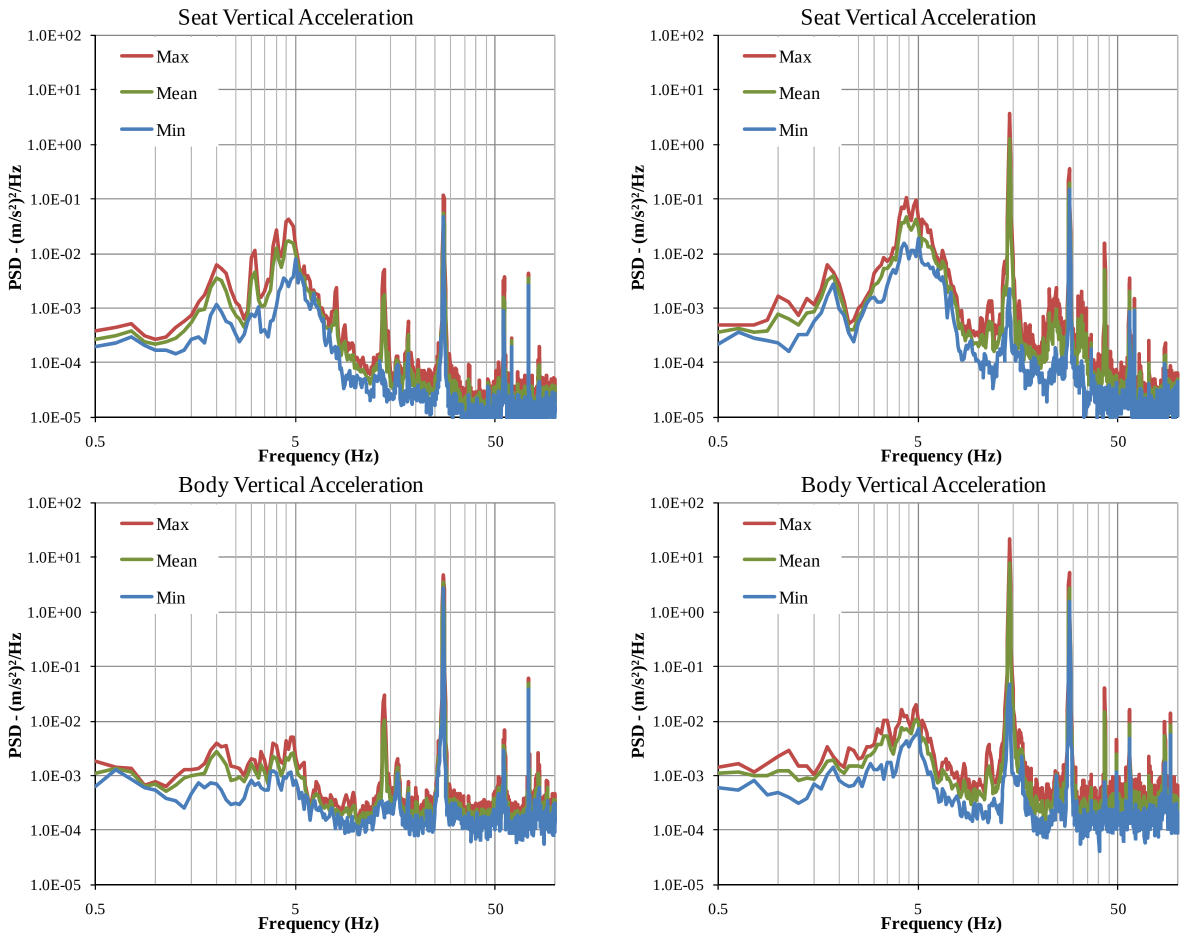
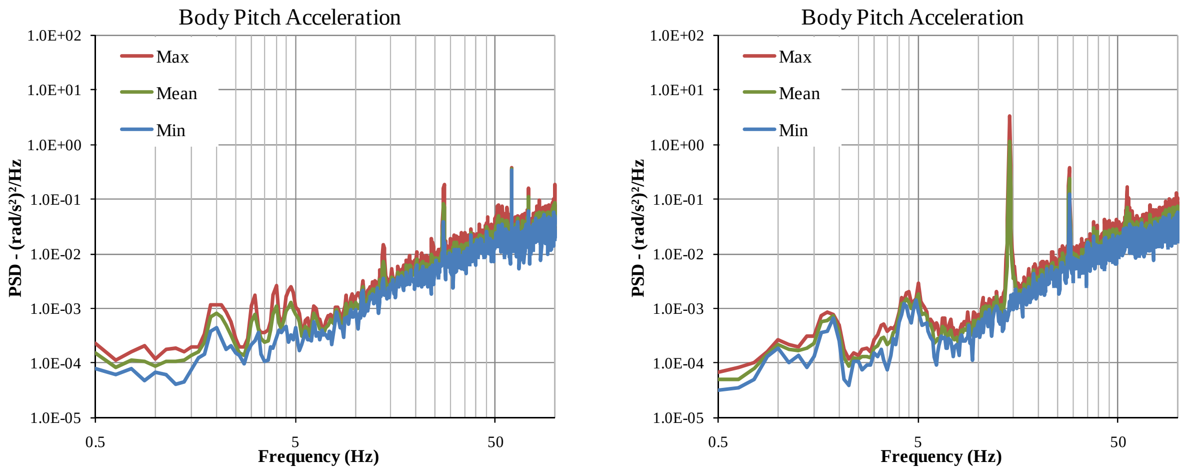


Figure A.7: Ranges of PSD of lateral (y) acceleration measured at the seat and vehicle body during high-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



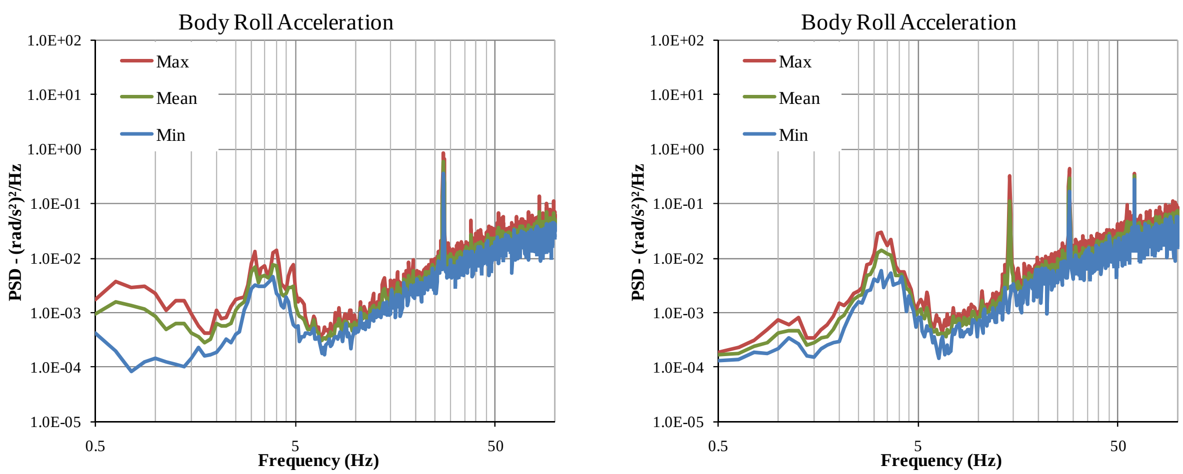
(a) **(b)**

Figure A.8: Ranges of PSD of vertical (z) acceleration measured at the seat and vehicle body during high-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



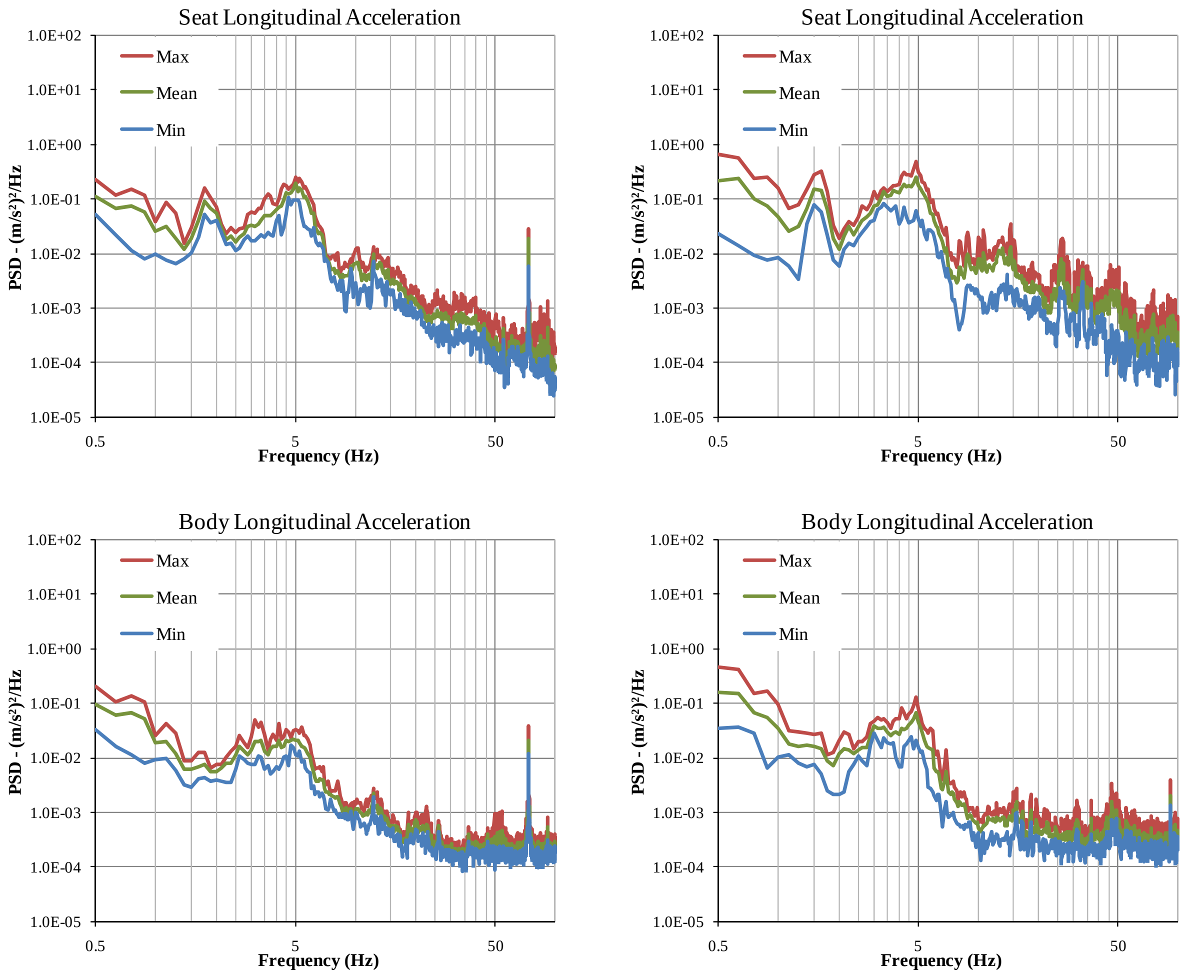
(a) **(b)**

Figure A.9: Ranges of PSD of pitch (θ) acceleration measured at the vehicle body during high-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



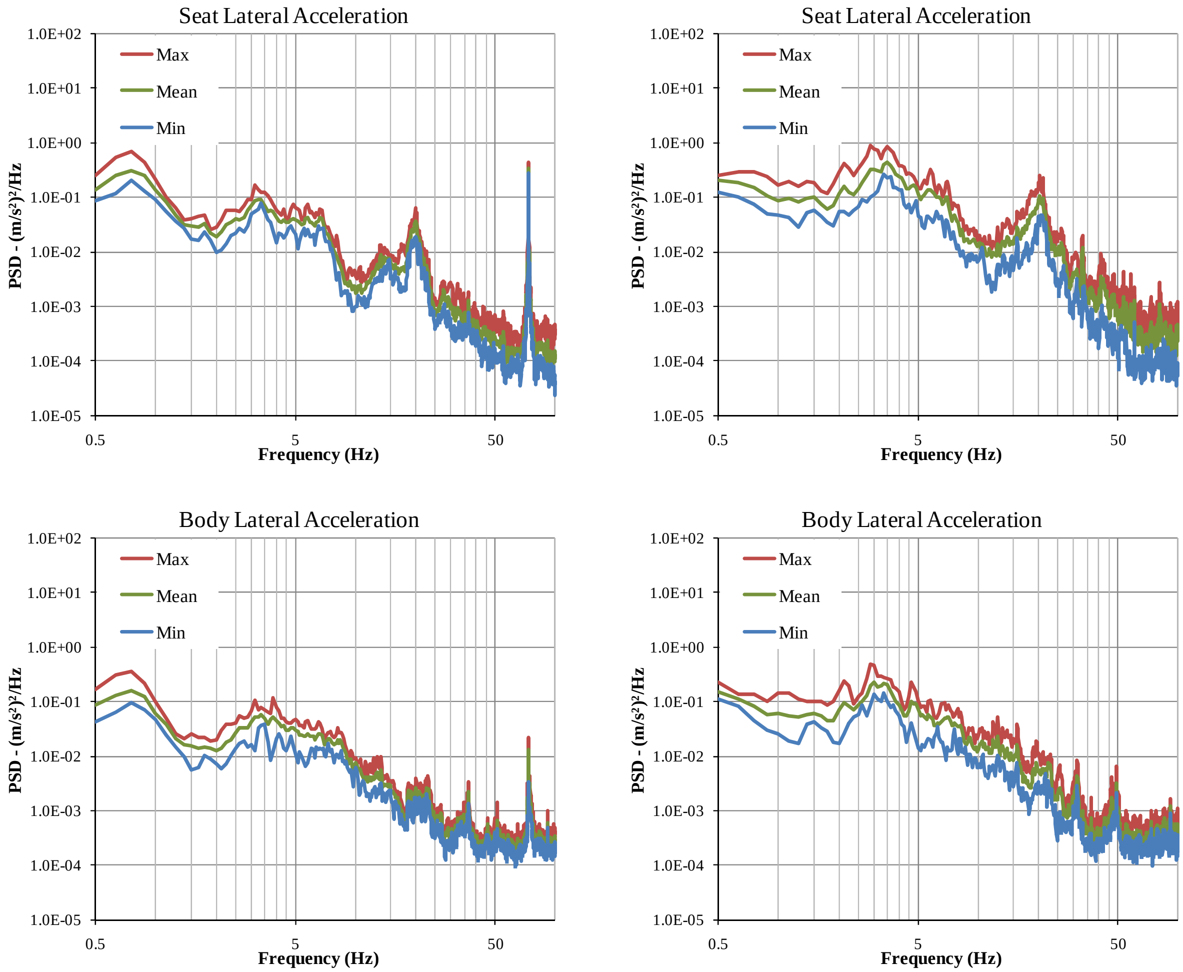
(a) **(b)**

Figure A.10: Ranges of PSD of roll (φ) acceleration measured at the vehicle body during high-density soil compaction: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



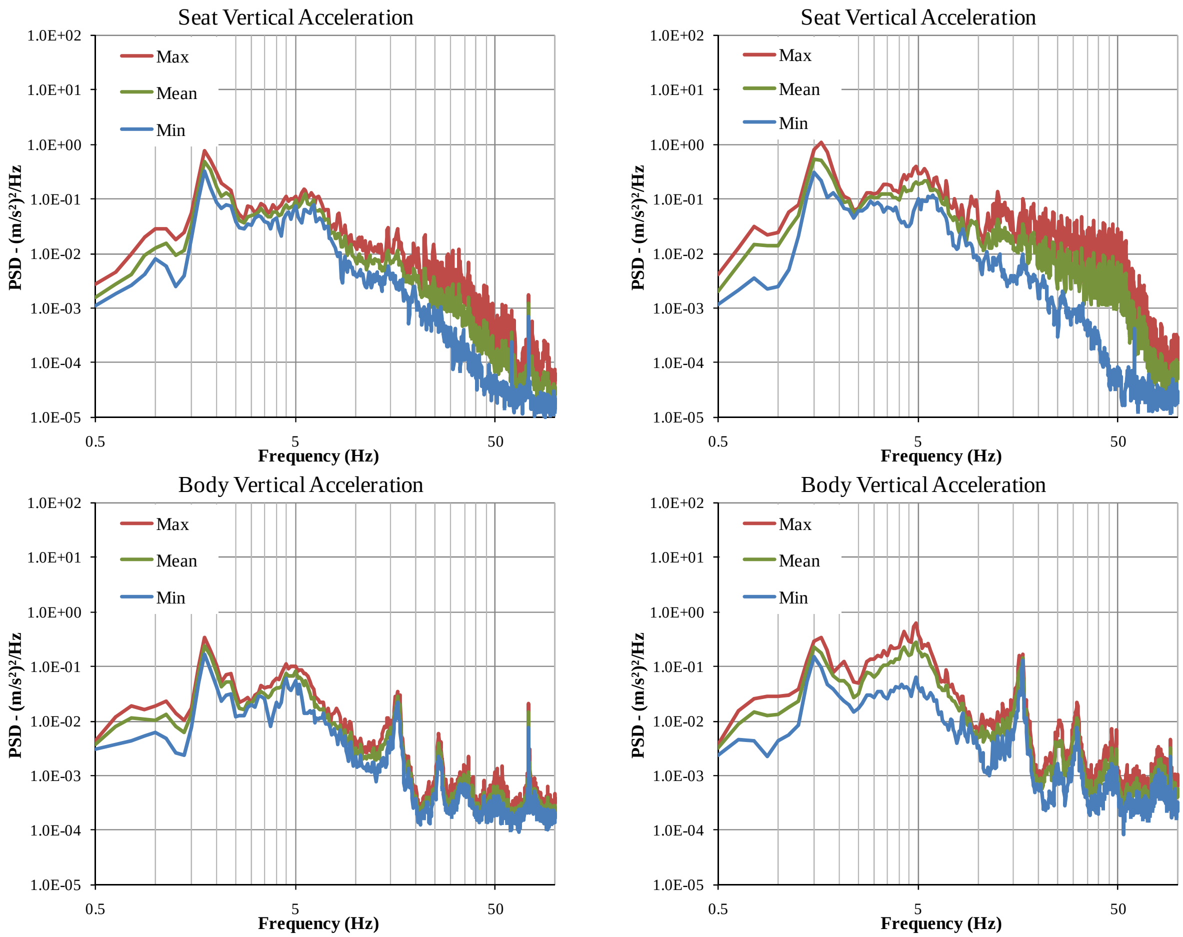
(a) **(b)**

Figure A.11: Ranges of PSD of longitudinal (x) acceleration measured at the seat and vehicle body during transit: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



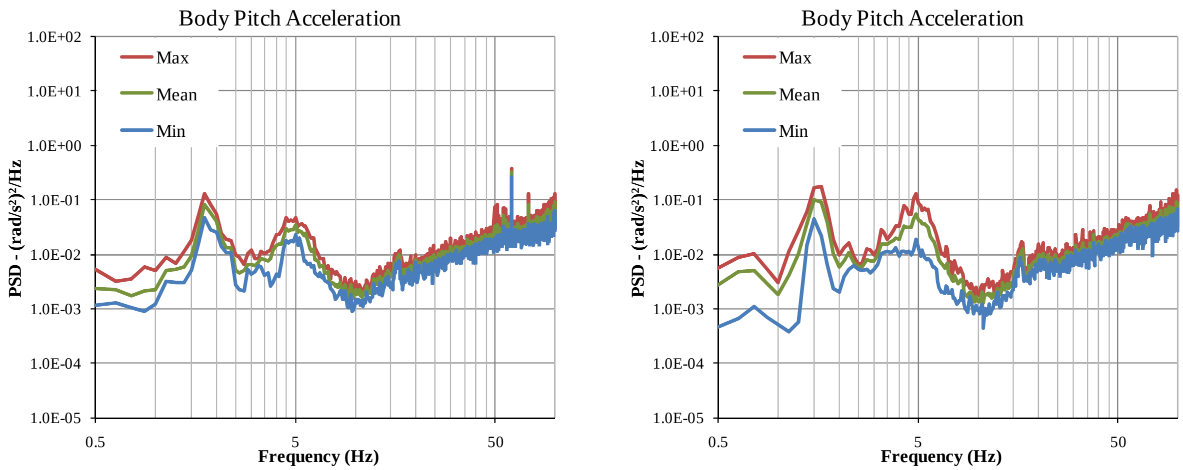
(a) **(b)**

Figure A.12: Ranges of PSD of lateral (y) acceleration measured at the seat and vehicle body during transit: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



(a) **(b)**

Figure A.13: Ranges of PSD of vertical (z) acceleration measured at the seat and vehicle body during transit: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.



(a) **(b)**

Figure A.14: Ranges of PSD of pitch (θ) acceleration measured at the vehicle body during transit: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.

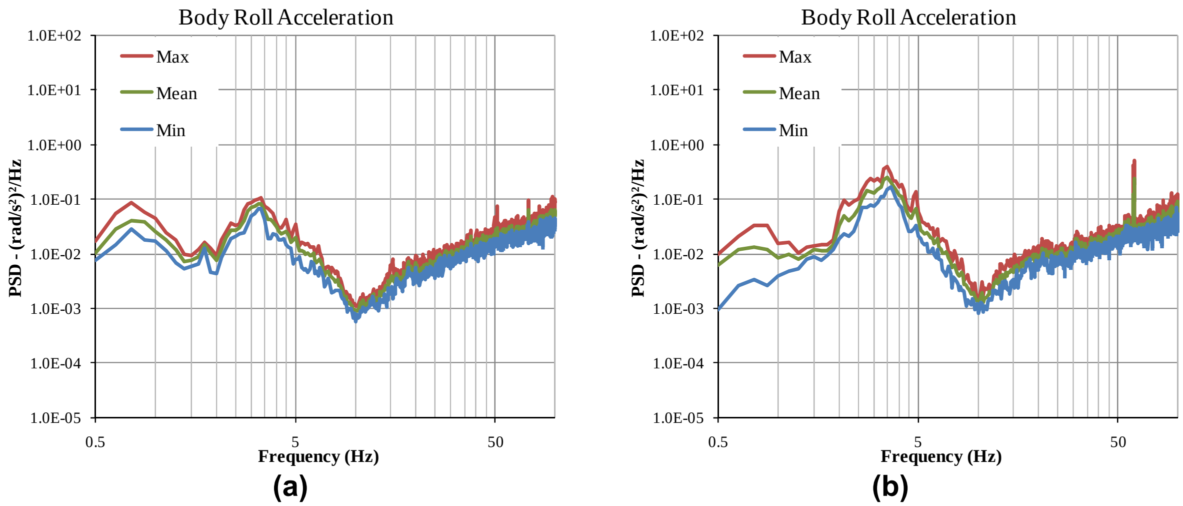
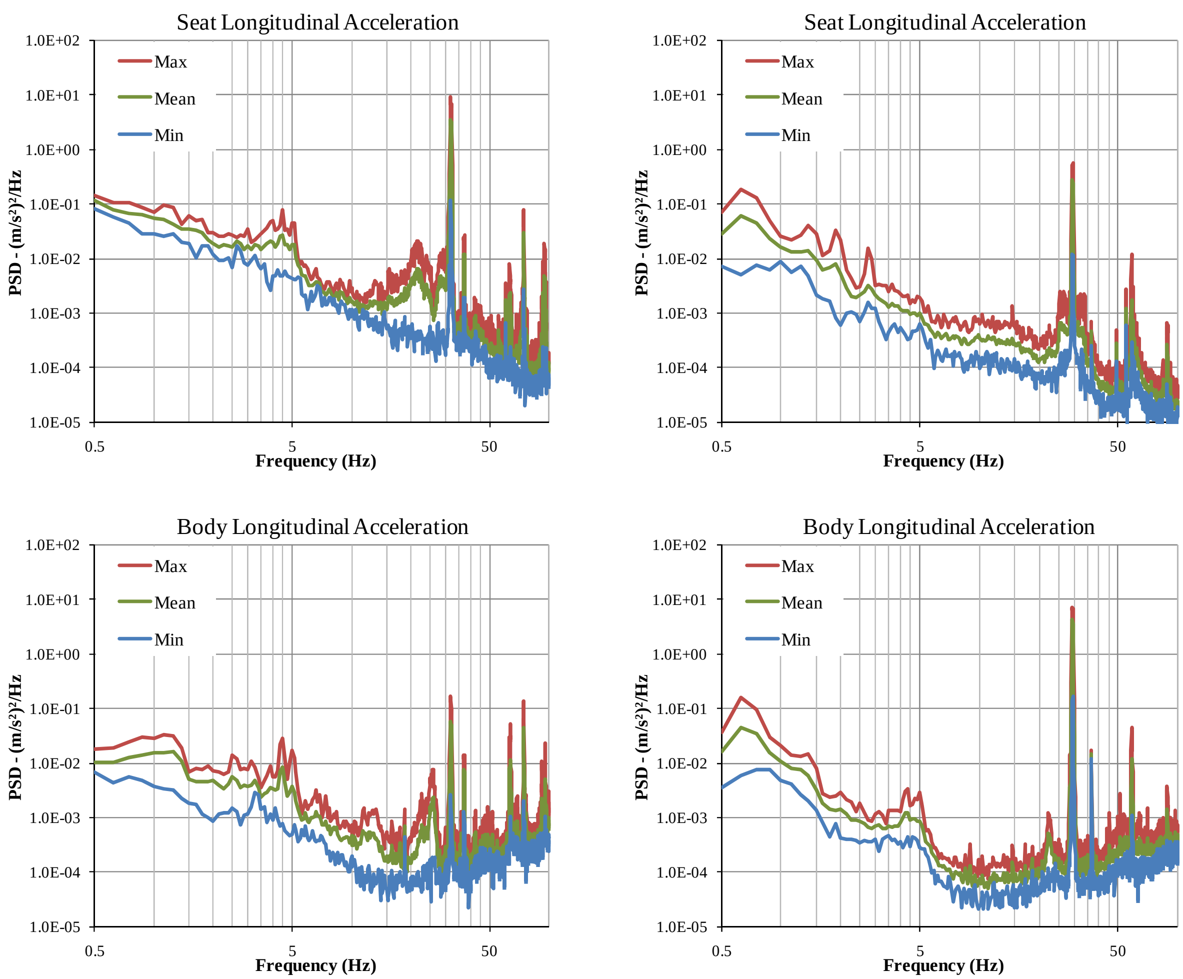


Figure A.15: Ranges of PSD of roll (φ) acceleration measured at the vehicle body during transit: (a) 10-ton 4-cylinder vehicle; and (b) 10-ton 6-cylinder vehicle.

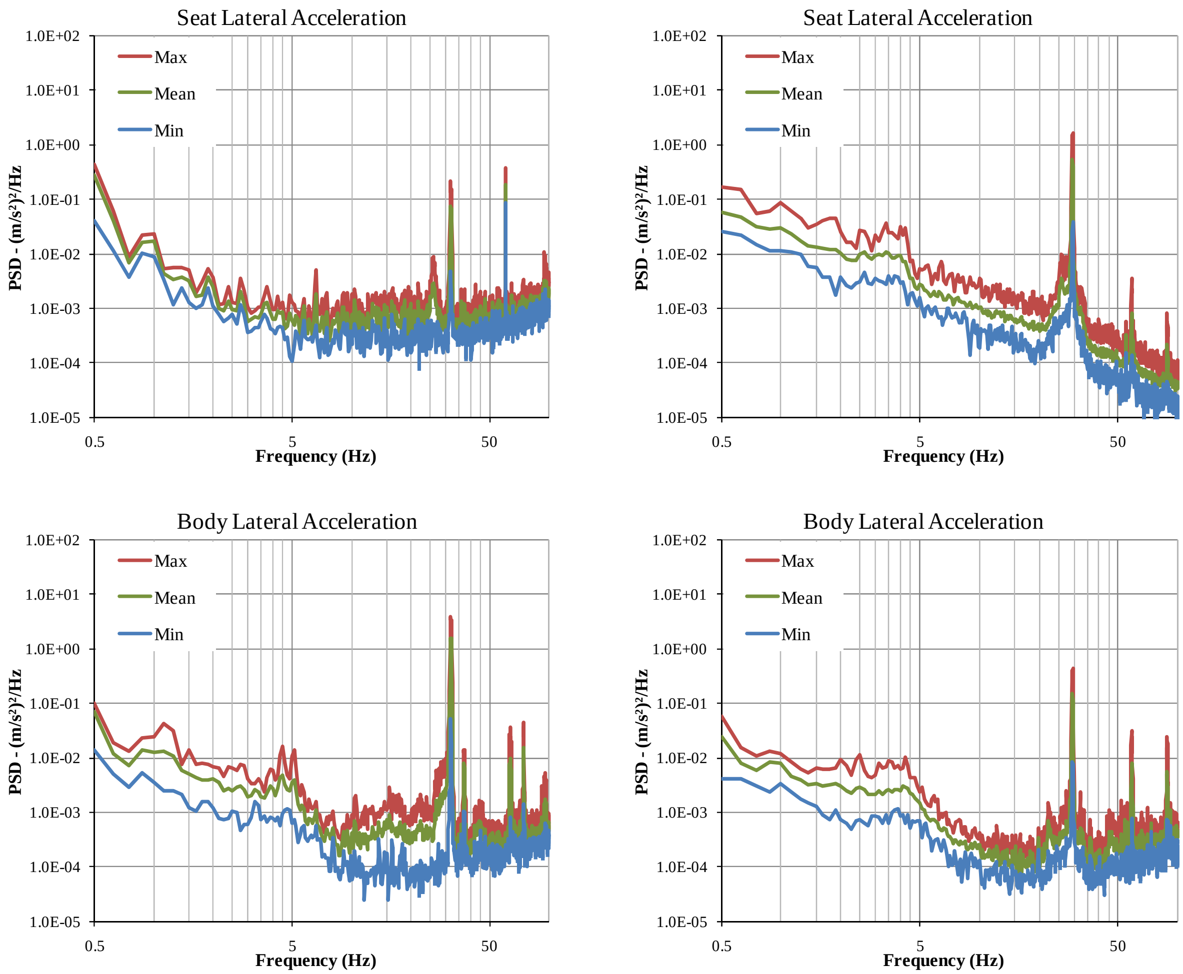
APPENDIX B

RANGES OF SPECTRA OF VIBRATION MEASURED COMPACTION AND TRANSIT TASKS AT WORKSITES



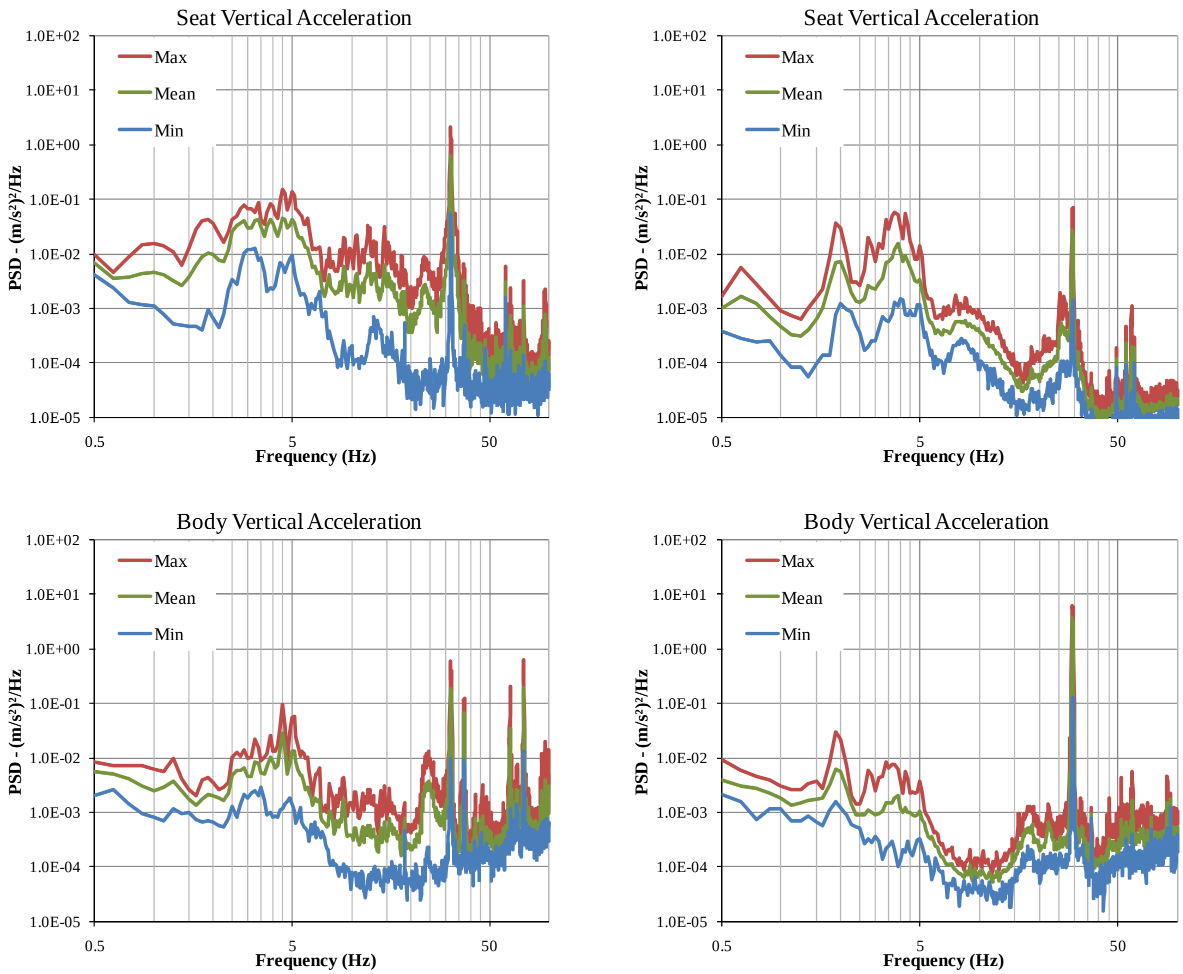
(a) **(b)**

Figure B.1: Ranges of PSD of longitudinal (x) acceleration measured at the seat and vehicle body during compaction at low vibrator amplitude: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.



(a) **(b)**

Figure B.2: Ranges of PSD of lateral (y) acceleration measured at the seat and vehicle body during compaction at low vibrator amplitude: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.



(a) **(b)**

Figure B.3: Ranges of PSD of vertical (z) acceleration measured at the seat and vehicle body during compaction at low vibrator amplitude: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.

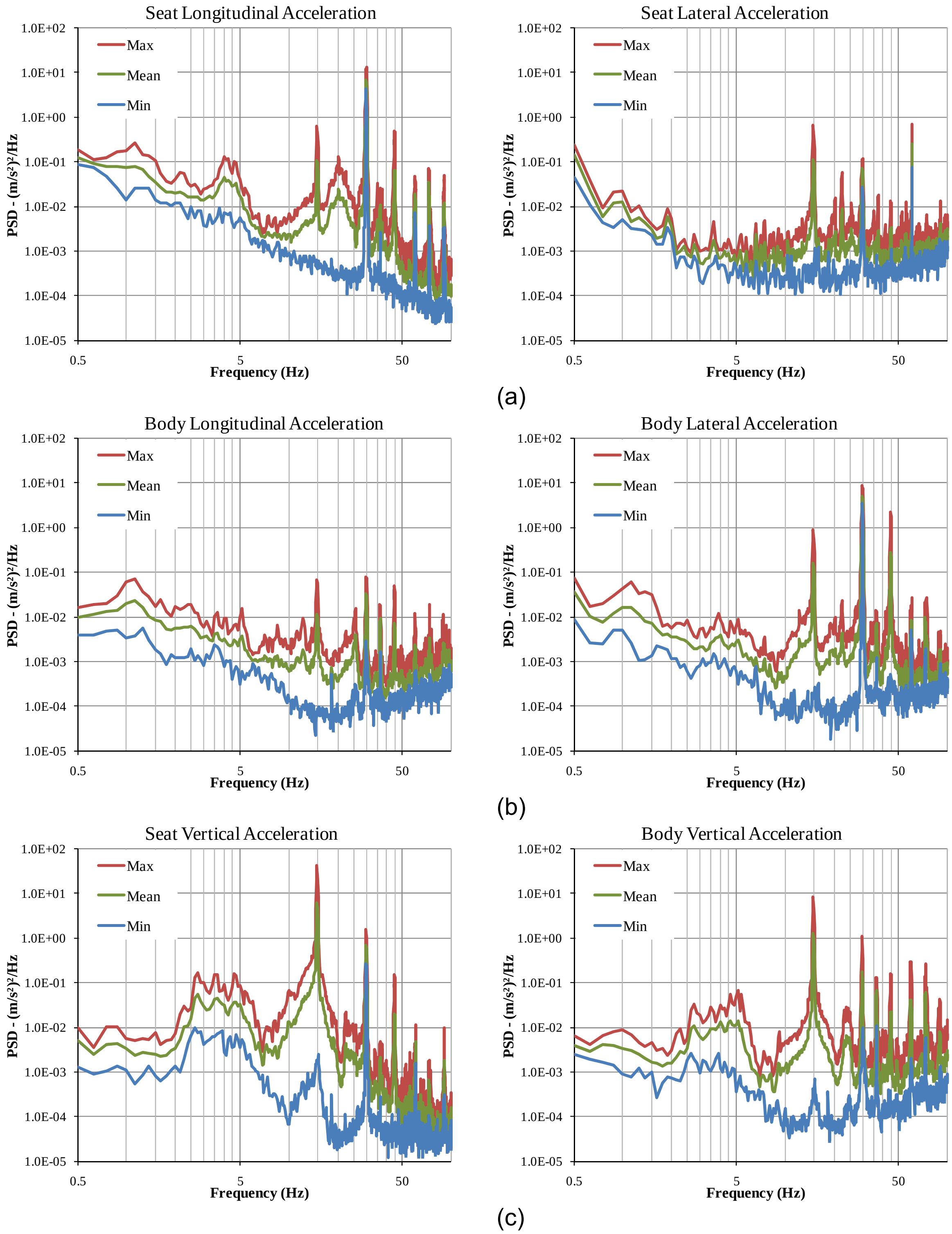
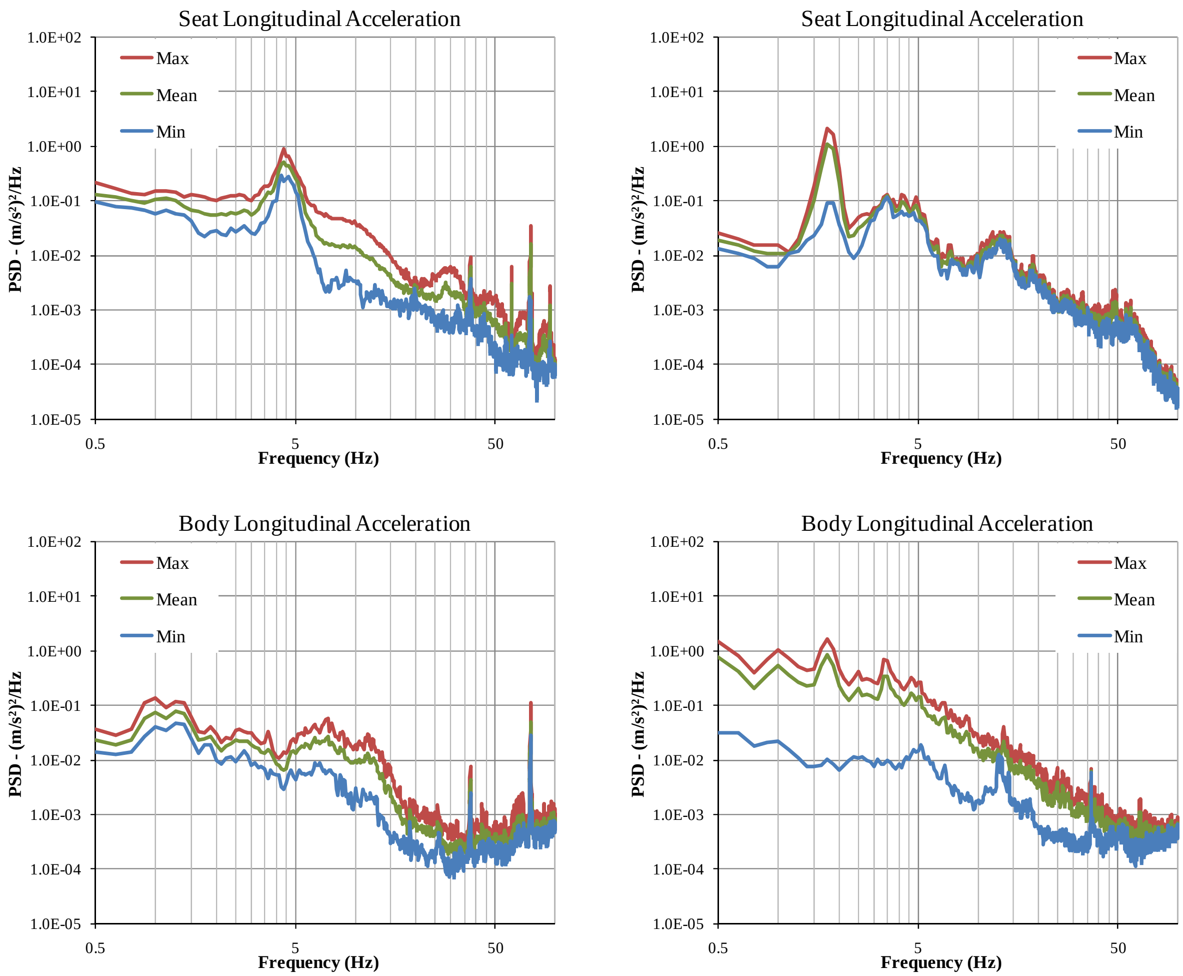


Figure B.4: Ranges of PSD of longitudinal (x), lateral (y) and vertical (z) acceleration measured at the seat and vehicle body during high amplitude compaction with the 10-ton 4-cylinder compactor: (a) longitudinal; (b) lateral; and (c) vertical.



(a) **(b)**

Figure B.5: Ranges of PSD of longitudinal (x) acceleration measured at the seat and vehicle body in the transit mode: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.

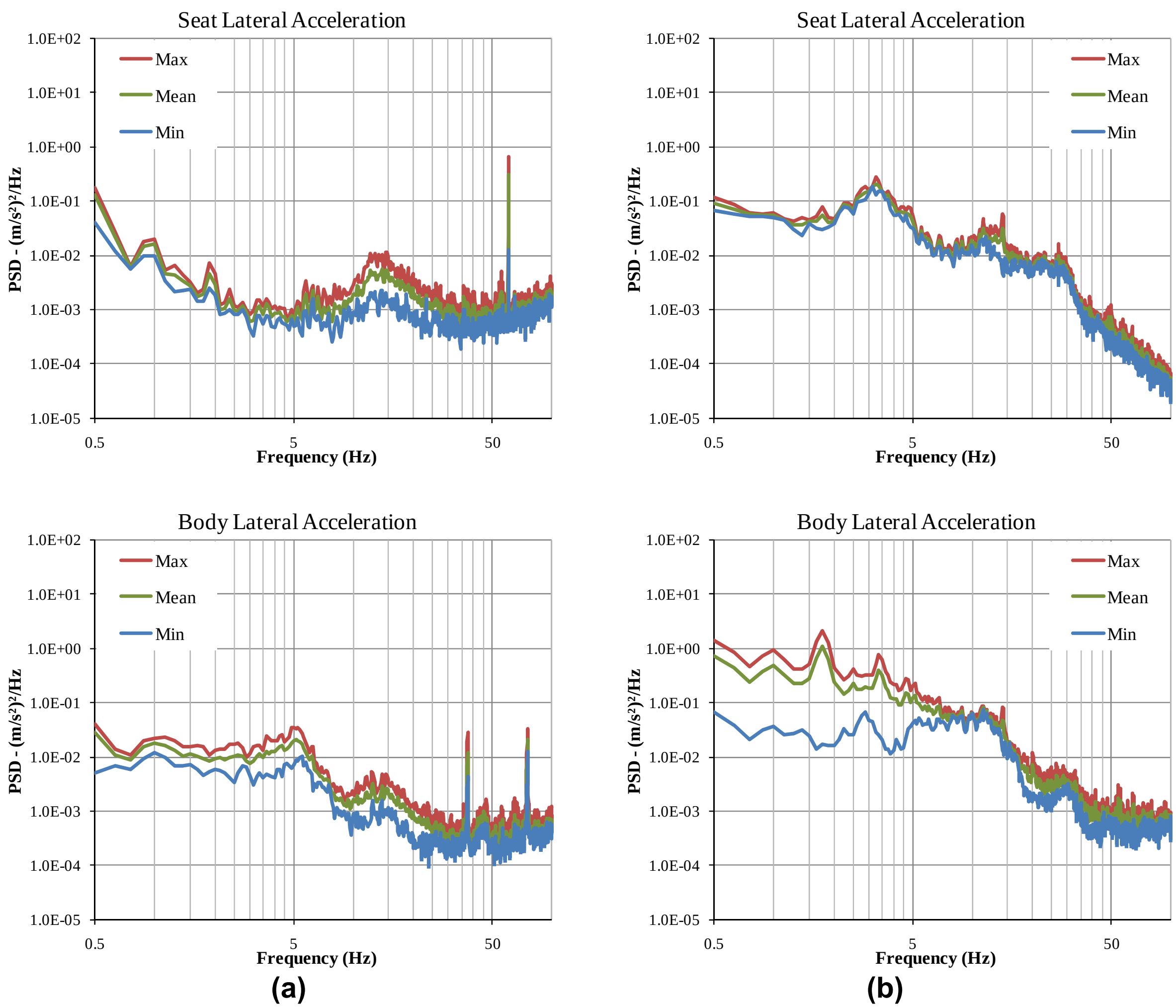


Figure B.6: Ranges of PSD of lateral (y) acceleration measured at the seat and vehicle body in the transit mode: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.

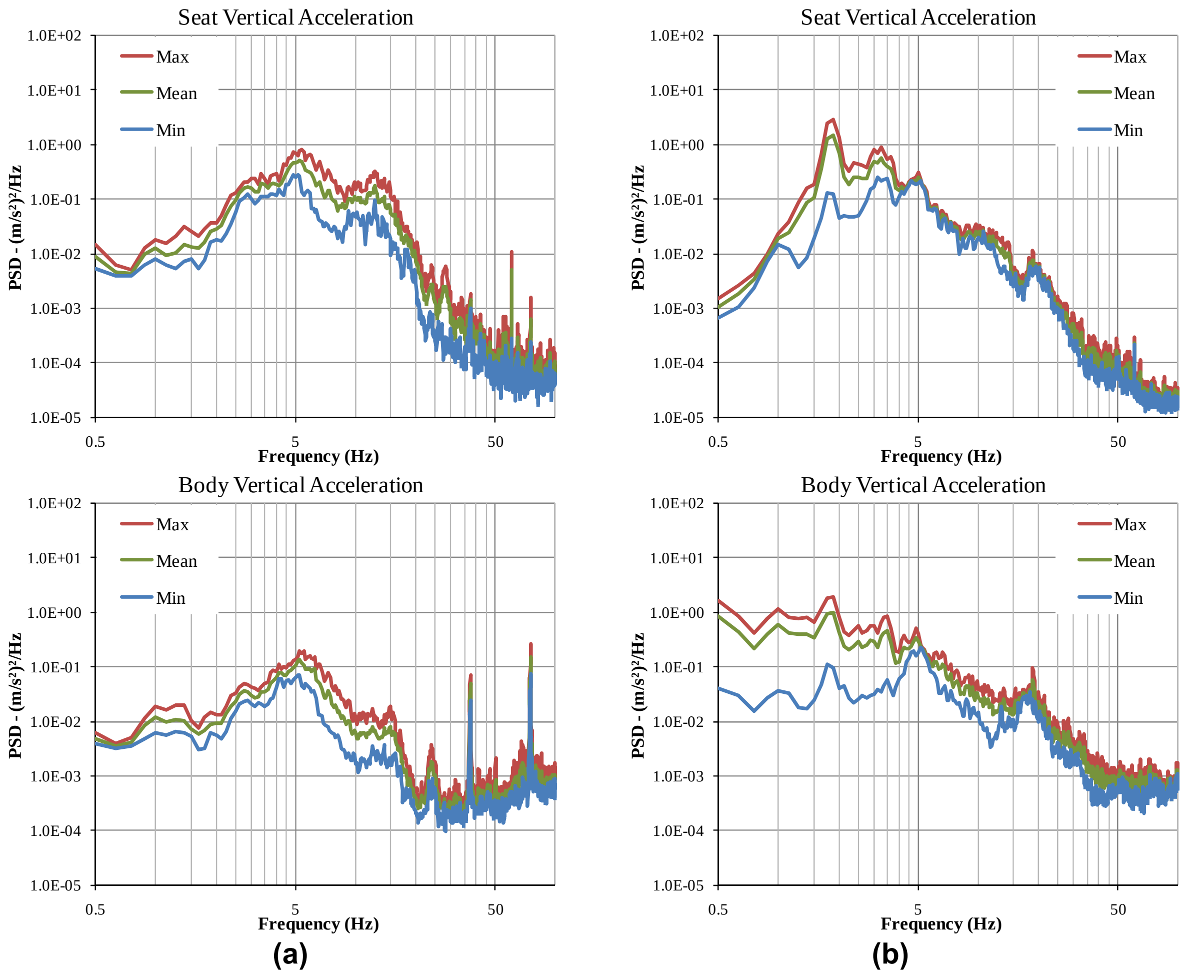


Figure B.7: Ranges of PSD of vertical (z) acceleration measured at the seat and vehicle body in the transit mode: (a) 10-ton 4-cylinder vehicle; and (b) 13-ton 6-cylinder vehicle.