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# Contribution of individual components of a job cycle on overall severity of whole-body vibration exposure: a study in Indian mines

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Abstract:

Drivers of earth-moving machines are exposed to whole-body vibration (WBV). In mining operations there can be a combination of relatively high magnitudes of vibration and long exposure times. Effective risk mitigation requires understanding of the main aspects of a task that pose a hazard to health. There are very few published studies of WBV exposure that have been carried out in India. This paper reports a study that considered the contribution of the component phases of dumper operations, on the overall vibration exposure of the drivers. It shows that vibration magnitudes are relatively high, and that haulage tasks are main contributor to the exposure. It is recommended that driver speed, haul road surfaces and vehicle maintenance/selection are optimised to ensure minimisation of vibration. If this is not sufficient, operation times might need to be reduced in order to ensure that the health guidance caution zone from Standard No. ISO 2631-1:1997 is not exceeded.

Keywords: **whole-body vibration; Job safety analysis; Physical hazards in mining**

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## 1.0 Introduction

Methods for prediction of the health risk arising out of exposure to whole-body vibration (1–80 Hz) at work are primarily based on two parameters, namely, (a) acceleration transmitted to human body part in contact with the vibration source and (b) duration of such exposure. As described in Standard No. ISO 2631-1:1997, the basic evaluation process depends on rms values of frequency-weighted acceleration measured over a day-long period or a shorter period where the short period of measurement is considered to be representative of the exposure. In cases where the job carried out by a person is cyclic in nature, it is convenient to measure the magnitude of acceleration for one cycle of such operation and use that value for risk prediction models. The duration of exposure, in such cases, will be the product of the time taken for one cycle and number of such cycles completed in a day. This means that the total exposure contains a series of, or several repetitions of, shorter exposures of the same severity which is generally considered a reasonable assumption. The same principle can be applied if vibration dose values (VDV) are used for risk evaluation; of course in such cases the total VDV needs to be computed with appropriate mathematical relations [1,2].

Previous studies have considered the respective vibration magnitudes experienced by drivers during different phases of a work operation. For example, Eger et al. [3,4] considered factors that affect the overall exposure of workers to WBV and demonstrated that smooth terrain, low speed, loaded with 'ride control' was the optimal configuration for load-haul-dump trucks (LHDs). For tracked loaders, Newell et al. [5] also showed an effect of task type on the vibration emission (considering loading, levelling, and transport), and also concluded that driver speed and therefore training were important factors in mitigation of the health risk of exposure to WBV. Detailed modelling of vibration characteristics has been achieved for non-earth moving applications. Kåsin et al. [6] performed detailed analyses of vibration characteristics for helicopters and, through modelling of flight patterns, were able to predict the overall vibration exposure for helicopter pilots.

Understanding the vibration exposure of vehicle occupants is important in understanding the root causes of risk, and enabling engineers to reduce risk with the help of either technical interventions or modifications in work practices [7]. Few studies have been found that break up jobs into smaller segments and look into the individual contribution of the segments on to the overall severity of the exposure for large dumpers. The present study aims to look into the various stages of operation of a fleet of 100-t dumpers deployed in a large mechanized metal mine in western India for transportation of ore and overburden. The transportation job has been conceived of having four modular components: loading, hauling, unloading and return to the loading point thus defining a cycle. This modular approach is designed in order to gain an additional perspective to bring out certain factors which might be easily controlled to reduce the magnitude of vibration and thereby reducing the risk of musculoskeletal disorders associated with operation of dumpers. This is the first paper that reports such data collected in an Indian mine.

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## 2.0 Methodology

### 2.1 Work phase analysis

Dumpers are regularly and extensively used for transportation of coal, minerals and overburden in opencast mines. Factors like rugged/uneven terrain, driving speed, condition of seat and suspension, loading, etc. are responsible for vibration of the dumpers during operation. The vibration energy is transmitted to the human body mainly through the seat of the operator.

To recognize individual contribution of various components of a job cycle and its effect on peak acceleration as well as on overall rms acceleration values, studies were conducted on movement of eight dumpers. These dumpers were transporting ore from various benches of an opencast mine to their dumping point (Table 1). Shovels were deployed for loading the blasted ore from the mining benches to the dumpers. Dumpers 201 and 203 were engaged in pit bottom and took more time for onward as well as return journey on the haul road. All these dumpers were of the same make, capacity (100 t) and year of commissioning (2008). With a view to record various activities performed at various stages of the operation, time taken for each distinct segment of the transportation process as well as to study the characteristics of vibration emission of the dumpers at each of these phases, the job cycle was subdivided into the following components:

- **Loading**: In this initial phase, dumpers are in a stationary condition. Vibration is generated from the top of the vehicle due to impacts from rocks that have been released from the shovel bucket landing in the dumper bucket resulting in primarily vertical ($z$) and lateral oscillations ($y$).
- **Transportation (hauling)**: In this phase, the loaded dumper travels over the haul road towards the dumping point. Vibration is transmitted through the seat due to road tyre interaction during movement over the haul road which may vary in inclination, turning radius, degree of roughness and undulations. Note that as each dumper was working in a different part of the mine, the overall times to completion would not be expected to be identical.
- **Unloading (dumping):** This takes place at crusher hopper or temporary stockpile area where the loaded material is removed from the dumper. Vibration is generated due to short maneuvering movements of the dumper to orientate it for unloading. Unloading of materials involves lifting of the bucket to an inclined position followed by removal of load by gravitational flow of rocks (which may not be uniform) and finally resetting the bucket on the chassis collapsing the dump cylinder.
- **Return journey:** In this part of the work the dumper moves unloaded over the haul road again for coming back to loading point. As a result, vibration is transmitted through the seat due to road tyre interaction during movement over the haul road which may vary in inclination, turning radius, degree of roughness and undulations.

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## 2.2 Instrumentation for vibration measurement

Advanced vibration analyzer SVAN 958 was used to record the acceleration in three axes during the operating cycle of the dumpers. Seat pad accelerometers were placed on the seat of the dumpers as described in Standard No. ISO 2631-1:1997[8]. Time markers were inserted in their movement history. These time markers separated and divided the time history in four distinct segments thus enabling the observer to study a number of significant parameters contributing and finally leading to the overall values that determine their hazard potential. SVAN 958 offers the facility to select a part of the time history and calculate Peak values and rms values of acceleration for that particular part along any axis. For technical reasons it was not possible to log driving speed. However, for safe operation, driving downhill had a speed limitation of 6 km/h. The observer sat on the helper's seat beside the driver and closely observed the movement of the driver as well as data updates on the display throughout the cycle of operation so as to identify any action or reason which may cause wrong representation of vibration data. For administrative limitations measurements could not be repeated on individual machines.

## 2.3 Ethical clearance

This study was approved by the Institutional Ethics Committee (IEC) of National Institute of Miners' Health, India. Purpose of the study was explained to the operators in local language and they gave informed consent for participation in the study.

## 3.0 Results and discussion

The rms and peak vibration data showed clear differences in the nature of the vibration and the magnitude of the vibration in each work phase (Figure 1; Figure 2). Each vehicle showed similar characteristics during each phase.

FIGURE 1 ABOUT HERE

FIGURE 2 ABOUT HERE

## 3.1 Vibration measured during haul road operations

Table 1 shows the time taken for each of four modular activities by all the dumpers. In all eight cases the time taken for return journey was less than time taken during onward journey of loaded dumper towards dumping point. It can be reasonably assumed that in most cases both the journeys had traced the same path of the haul road for an individual dumper. The mean return speed (unloaded) was found to be, on average, 42% higher than mean speed during the journey whilst loaded. Dumper 306



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which was engaged in removal of overburden (OB) from OB bench to the OB dump area showed a large difference in travel times but inspection of vibration profiles do not show a clear reason of why. If data from Dumper 306 is excluded, the difference between driving loaded and unloaded was reduced to 25%.

TABLE 1 ABOUT HERE

Root mean square values of acceleration for all four segments of the cycle were computed separately using logger files and the dominant axes during the four phases are presented in Table 2. It was observed that z direction was dominant in both hauling and return phases of transportation cycle.

Frequency-weighted rms values of acceleration ($a_w$) for the entire transportation job along all three axes before and after using the directional coefficient are presented in Table 3 ($k$ = 1.4 for $x$ and $y$ axes, $k$ = 1 for $z$ axis). Analysing the entire transportation cycles for all these eight dumpers, $z$ axis (vertical) was found to be dominant in all cases. Hence the acceleration values along the z axis of all these dumpers were directly used for all subsequent analysis since the Standard No. ISO 2631-1:1997 multiplication factor ($k$) for $z$ axis is 1. Since the operators spent most of their time for movement over the haul road, vertical axis z emerged as the dominant axis even though loading and unloading operations caused the other to axes ($x$ and $y$) to record larger acceleration magnitudes (see section 3.2).

It is evident from the above rms values of acceleration for four different components of the transportation job that mean rms acceleration during return journey of empty dumpers was about 28% more than that during journey with load (Table 4). Therefore the combination of higher vehicle speed and no load during return journey played an important role in the overall severity of exposure of the operator. The nature of the job requires return to the site of mineral/overburden extraction unloaded, and therefore altering the load is an impractical method of vibration reduction. Hence speed regulation is the only controllable factor when other parameters are unchanged. Slower speed driving would reduce the vibration exposure of the operators. As shown by a previous study [9] conducted in a mine, speed of a dumper on a haul road was found to have direct bearing on the intensity of vibration along $z$ axis (Figure 3), and has been previously shown by Eger et al. [3] and Newell et al. [5].

TABLE 2 ABOUT HERE

TABLE 3 ABOUT HERE

FIGURE 3 ABOUT HERE

Max Peak accelerations were observed to exceed 8 m/s$^2$ for all the dumpers during loaded journey on the haul road and on two instances it exceeded 10 m/s$^2$. Max Peak accelerations were also observed to exceed 10 m/s$^2$ for all the dumpers during the return journey (unloaded) and on five instances it exceeded 12 m/s$^2$. The maximum peak value reached 31 m/s$^2$ for dumper 107. Peaks in the vibration coincided with crossing over a crest or trough or negotiation of a sharp bend on the haul



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road without reducing the speed. Higher vibration levels during unloaded journey are also affected by the change in the vehicle dynamic e.g. change of the suspension loading.

## 3.2 Vibration measured during loading/unloading

During loading operation, the dumpers are parked at a loading point in a working face hence forward and lateral vibrations are minimal. Vibrations in *x* and *y* axes during loading is due to marginal oscillations of the dumper bucket in these directions. Most of the vibration energy comes from the mechanical shocks produced by the falling rocks or boulders on the bucket.

During unloading operation the dumper has to stop for a moment and move in the reverse direction slowly to position itself for safe unloading. The bucket is slowly lifted to release the material. The segment is shortest in terms of time taken by all the segments.

During loading and dumping operations, *x* and *y* were found dominant taking into consideration directional coefficient ($k$ = 1.4 for *x* and *y* axes and $k$ = 1 for *z* axis). Since the vibration generated during loading largely depends on the specific point of discharge of blasted rocks on the bucket (front, rear or on the sides), direction of dominant axis of vibration can change accordingly. Likewise, during unloading operation, due to slow movements towards front or rear direction to position the vehicle, *x* axis can emerge as dominant as shown in this study. (Table 2)

Dumper 306 was the slowest to be loaded, but the loading was regular, as shown by the sequence of peaks in the vibration time-histories. The time taken to load the dumpers varied from 86 to 459 s; the time taken to unload ranged from 24 to 41 s. There was no correlation between the time taken to load and the time taken to unload. The shovel operators take their own decisions during loading the blasted rock on to the dumpers depending on the size of the rocks available for loading. They also spend some time in clearing the work zone to facilitate easy and safe loading operation.

TABLE 4 ABOUT HERE

Vibration felt by the equipment operator during loading and unloading are lower than those that occur for hauling or returns (Table 4). Mean rms acceleration in *z* axis was 0.156 and 0.365 m/s$^2$ during loading and unloading, respectively.

Peak values during loading showed a large degree of variability. This variability was due to the size of boulders being loaded and the height from which they were released. Dumper 208 was loaded with large boulders and as a result the peak acceleration exceeded 6 m/s$^2$, the highest experienced during any of the trials. However, the peaks observed during loading were not as severe as the peaks measured during haulage. One operator in the mine had reported to have sustained low back injury due to shocks experienced during the loading process and required hospitalization. Some operators reported a desire to leave the dumper after positioning it for loading and stand away from the equipment to avoid such injury. This is not considered acceptable from a safety point of view as it increases the chance of injury from slipping and the proximity of boulders being dropped into the

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bucket during the process of loading, which could cause a hazard. A preferred solution is to reduce the maximum size of blasted rocks through better fragmentation. It should be noted that the method used in the risk assessment here is not optimized to shock-type signals. It might be better to use the methods described in Standard No. ISO 2631-5:2004 for such assessments [10].

### 3.3 Contribution to overall dose from component parts of dumper operation

The total exposures of the drivers can be calculated from the component parts of their job. If it is assumed that each driver works for 8 h per day, then the extrapolated vibration exposures ($A(8)$ values) are as shown in Table 5. Annex B of Standard No. ISO 2631-1:1997 defines a health-guidance caution zone (HGCZ) defined by values of $A(8)$ of 0.43 and 0.87 m/s² rms. The EU physical agents (vibration) directive defines an exposure action value (EAV) and exposure limit value (ELV) at 0.5 and 1.15 m/s² rms, respectively [8].

TABLE 5 ABOUT HERE

If drivers of these dumpers had vibration exposure for 8 h continually per day, then all would exceed the EAV but none would exceed the ELV, although this would be exceeded in 8 h 41 min for the worst machine/task combination. Half of the dumper/task combinations would exceed the upper limit of the Standard No. ISO 2631-1:1997 health guidance caution zone with 8 h of continual use. In practice, it is rare for drivers to be exposed to exactly 8 h of vibration due to breaks, or times waiting to be loaded/unloaded, refueling, maintenance and other activities. In contrast, many drivers may choose to work longer hours in order to work overtime or meet the requirements of their contract. Therefore it is necessary to carefully consider the working time in order to generate a full risk assessment.

The vibration exposures for drivers operating the machines in this study are relatively high and therefore it would be desirable to take action to minimize risk. The work-phase analysis used in this study allows for prioritization of those phases that constitute the most risk. Combining the exposure time and the vibration magnitude the hauling and return phases contribute 99% of the overall vibration dose (Figure 4). Therefore, for rms vibration exposure minimization, these should be prioritized. Improvements can be made through three approaches:

1. Improvement in maintenance of the haul roads. Ensuring that roads are kept smooth and free from discontinuities such as large pot holes.
2. Reduction in speed of the machine (see Figure 3).
3. Better maintenance of the machine, including the seat. If necessary, replacement of the machine.

Once action has been taken a further evaluation will need to be completed to ensure that the residual vibration exposure is acceptable; if not, then reductions in work times might be necessary.

FIGURE 4 ABOUT HERE

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## 4.0 Conclusion

During the transportation of either ore or overburden material, the overall vibration exposures was dominated by their movements during hauling and return journeys on the haul road. Apart from the technical measures of reducing the severity of exposure, such as modification of seat and suspension systems, haul road conditions need to be maintained regularly and speed limitations are a must as is shown by this study. Separation of various components of a job has undoubtedly provided a better tool for introspective study on vibration characteristics of a job cycle. It has also shown that dominant axis of vibration can vary within various segments of a job cycle. Similar approach can be applied to other jobs which are far more complicated and effective monitoring and control strategies can be developed with the method suggested. Identification of the most significant contributors to a vibration exposure allows for targeted risk management strategies.

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**References**


1. Mandal BB, Srivastava A. Musculoskeletal disorders in dumper operators exposed to whole body vibration at Indian mines. International Journal of Mining, Reclamation and Environment. 2010;24:233–243.
2. Mansfield NJ. Human response to vibration. Boca Raton, Florida: CRC Press; 2005.
3. Eger TR, Contratto MS, Dickey JP. Influence of driving speed, terrain, seat performance and ride control on predicted health risk based on ISO 2631-1 and EU Directive 2002/44/EC. Journal of Low Frequency Noise, Vibration and Active Control. 2011;30(4):291-312.
4. Eger T, Stevenson J, Boileau PÉ, Salmoni A. Predictions of health risks associated with the operation of load-haul-dump mining vehicles: Part 1—Analysis of whole-body vibration exposure using ISO 2631-1 and ISO-2631-5 standards. International journal of industrial ergonomics. 2008;38(9):726-738.
5. Newell GS, Mansfield NJ, Notini L. Inter-cycle variation in whole-body vibration exposures of operators driving track-type loader machines. Journal of sound and vibration. 2006; 298(3): 563-579.
6. Kasin JI, Mansfield N, Wagstaff A. Whole body vibration in helicopters: risk assessment in relation to low back pain. Aviation, space, and environmental medicine. 2011;82(8):790-796.
7. Mandal BB, Sarkar K, Manwar V. A study of vibration exposure and work practices of Loader and Dozer operators in opencast mines. International Journal of Occupational Safety and Health. 2012;2(2):3-7.
8. International Organization for Standardization (ISO). Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 1: General requirements (Standard No. ISO 2631-1:1997). Geneva, Switzerland: ISO; 1997.
9. Mandal BB. Development of a protocol for evaluation of vibration hazard potential of mining and processing equipment [unpublished doctoral dissertation]. Indian School of Mines, Dhanbad, India; 2013.
10. International Organization for Standardization (ISO). Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 5: Method for evaluation of vibration containing multiple shocks (Standard No. ISO 2631-5:2004). Geneva, Switzerland: ISO; 2004.


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**Table 1: Time taken by various activities during transportation**

| Dumper | Loading (s) | Hauling (s) | Dumping (s) | Return (s) |
|---|---|---|---|---|
| 101 | 101 | 486 | 29 | 409 |
| 105 | 131 | 555 | 24 | 538* |
| 107 | 86 | 623 | 27 | 495 |
| 201 | 196 | 1059* | 41 | 838 |
| 203 | 163 | 1035 | 36 | 783* |
| 208 | 190 | 969 | 36 | 692 |
| 303 | 124 | 484 | 38 | 404 |
| 306 | 459 | 1055 | 25 | 259 |
| *M* | 181 | 783 | 32 | 552 |

Note: * = deducting idle time spent on haul road due to any traffic congestion

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**Table 2: Dominant axis at different phases of the transportation cycle**

| Dumper | Segment of job cycle | | | |
|---|---|---|---|---|
| | **Loading** | **Hauling** | **Dumping** | **Return** |
| 101 | *z* | *z* | *x* | *z* |
| 105 | *x* | *z* | *x* | *z* |
| 107 | *z* | *z* | *z* | *z* |
| 201 | *z* | *z* | *z* | *z* |
| 203 | *x* | *z* | *y* | *z* |
| 208 | *z* | *z* | *x* | *z* |
| 303 | *z* | *z* | *z* | *z* |
| 306 | *x* | *z* | *z* | *z* |

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**Table 3: Determination of dominant axis of frequency-weighted rms acceleration (m/s$^2$)**

| Dumper | $a_w$ | | | $a_w$ (after multiplying with sum factor) | | | Dominant axis | $a_w$ (dominant axis) |
|---|---|---|---|---|---|---|---|---|
| | *x* | *y* | *z* | *x* | *y* | *z* | | |
| 101 | 0.47 | 0.34 | 1.05 | 0.66 | 0.47 | 1.05 | *z* | 1.05 |
| 105 | 0.48 | 0.42 | 0.85 | 0.65 | 0.59 | 0.85 | *z* | 0.85 |
| 107 | 0.50 | 0.34 | 0.92 | 0.70 | 0.48 | 0.92 | *z* | 0.92 |
| 201 | 0.37 | 0.35 | 0.74 | 0.52 | 0.49 | 0.74 | *z* | 0.74 |
| 203 | 0.47 | 0.33 | 0.71 | 0.66 | 0.46 | 0.71 | *z* | 0.71 |
| 208 | 0.54 | 0.48 | 1.10 | 0.76 | 0.67 | 1.10 | *z* | 1.10 |
| 303 | 0.47 | 0.32 | 0.90 | 0.66 | 0.45 | 0.90 | *z* | 0.90 |
| 306 | 0.35 | 0.30 | 0.81 | 0.49 | 0.42 | 0.81 | *z* | 0.81 |

**Note:** $a_w$ = frequency-weighted rms values of acceleration.

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**Table 4: Frequency-weighted rms acceleration ($m/s^2$) for various activities during transportation along dominant axis ($z$)**

| Dumper | Loading ($m/s^2$) | Hauling ($m/s^2$) | Dumping ($m/s^2$) | Return ($m/s^2$) |
|---|---|---|---|---|
| 101 | 0.158 | 1.001 | 0.451 | 1.257 |
| 105 | 0.139 | 0.824 | 0.460 | 1.013* |
| 107 | 0.220 | 0.865 | 0.328 | 1.083 |
| 201 | 0.152 | 0.737* | 0.258 | 0.841 |
| 203 | 0.123 | 0.693 | 0.264 | 0.828* |
| 208 | 0.211 | 1.024 | 0.327 | 1.354 |
| 303 | 0.123 | 0.834 | 0.327 | 1.140 |
| 306 | 0.126 | 0.871 | 0.508 | 1.219 |
| *M* | 0.156 | 0.856 | 0.365 | 1.092 |

Note: * = ignoring idle time on haul road due to traffic congestion

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**Table 5: Overall vibration magnitudes and time to exposure thresholds**

| Dumper | Cycles in 8 h | $A(8)$ in 8 h (m/s²) | Time to HGCZ-l (h:min:s) | Time to HGCZ-u (h:min:s) | Time to EAV (h:min:s) | Time to ELV (h:min:s) |
|---|---|---|---|---|---|---|
| 101 | 28.1 | 1.055 | 01:19:41 | 05:26:12 | 01:47:44 | 09:29:57 |
| 105 | 23.1 | 0.866 | 01:58:16 | 08:04:09 | 02:39:55 | 14:05:56 |
| 107 | 23.4 | 0.925 | 01:43:41 | 07:04:24 | 02:20:11 | 12:21:33 |
| 201 | 13.5 | 0.742 | 02:41:10 | 10:59:44 | 03:37:54 | 19:12:44 |
| 203 | 14.3 | 0.718 | 02:52:19 | 11:45:24 | 03:52:59 | 20:32:31 |
| 208 | 15.3 | 1.103 | 01:12:55 | 04:58:28 | 01:38:35 | 08:41:29 |
| 303 | 27.4 | 0.909 | 01:47:24 | 07:19:41 | 02:25:13 | 12:48:14 |
| 306 | 16.0 | 0.817 | 02:13:06 | 09:04:50 | 02:59:57 | 15:51:58 |
| *M* | 20.1 | 0.892 | 01:58:34 | 08:05:21 | 02:40:19 | 14:08:03 |

Note: HGCZ = health guidance caution zone; HGCZ-l, HGCZ-u = HGCZ lower, upper limit [10]; EAV, ELV = exposure action value, exposure action limit value from EU physical agents (vibration) directive. EAV and ELV are stipulated by considering $A(8)$; $A(8)$ = 8-h exposure equivalent, which is derived with the equation:

$$A(8) = ka_w\sqrt{\frac{T}{T_0}},$$

where $a_w$ = measured rms vibration magnitude; $T$ = duration of exposure to the vibration magnitude $a_w$; $T_0$ = reference duration of 8 h; $k$ = multiplying factor ($k$ = 1.4 for $x$ and $y$ axes, 1.0 for $z$ axis).

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**Figure 1: Root mean square (rms) acceleration along *z* axis for all segments of job cycle: (a) dumper 101 (100 t), (b) dumper 105 (100 t), (c) dumper 203 (100 t), (d) dumper 208 (100 t), (e) dumper 107 (100 t), (f) dumper 201 (100 t), (g) dumper 303 (100 t), (h) dumper 306 (100 t).**

**Figure 2: Peak acceleration along *z* axis for all segments of job cycle: (a) dumper 101 (100 t), (b) dumper 105 (100 t), (c) dumper 203 (100 t), (d) dumper 201 (100 t), (e) dumper 107 (100 t), (f) dumper 201 (100 t), (g) dumper 303 (100 t), (h) dumper 306 (100 t).**

**Figure 3: Speed of dumpers versus rms acceleration [5].**
Note: $y = 0.0394\,x + 0.1251$, $R^2 = 0.9293$.

**Figure 4: Percentage contribution to overall vibration exposure for four different work phases of dumper operation**

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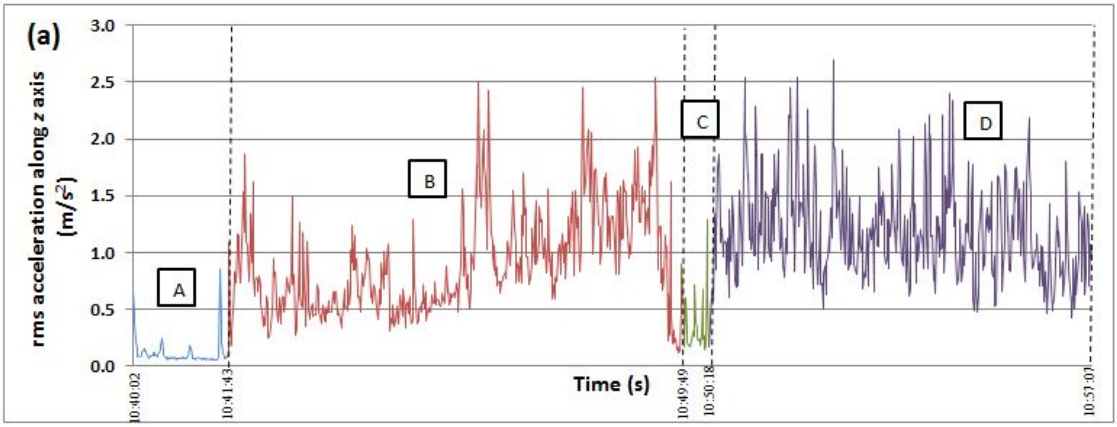


| A | B | C | D |
|---|---|---|---|
| loading | hauling | dumping | return |
| 101 s | 486 s | 29 s | 409 s |

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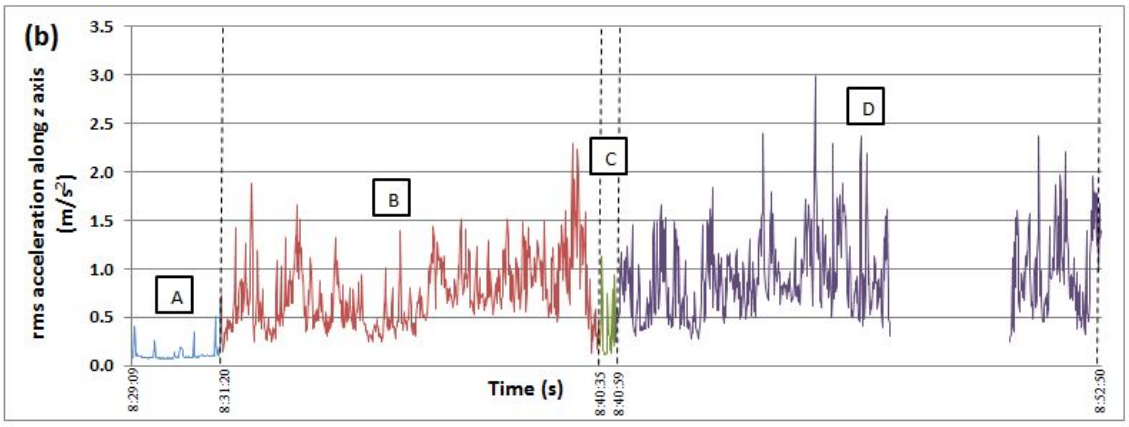


| A | B | C | D |
|---|---|---|---|
| loading | hauling | dumping | return |
| 131 s | 555 s | 24 s | 711 s |

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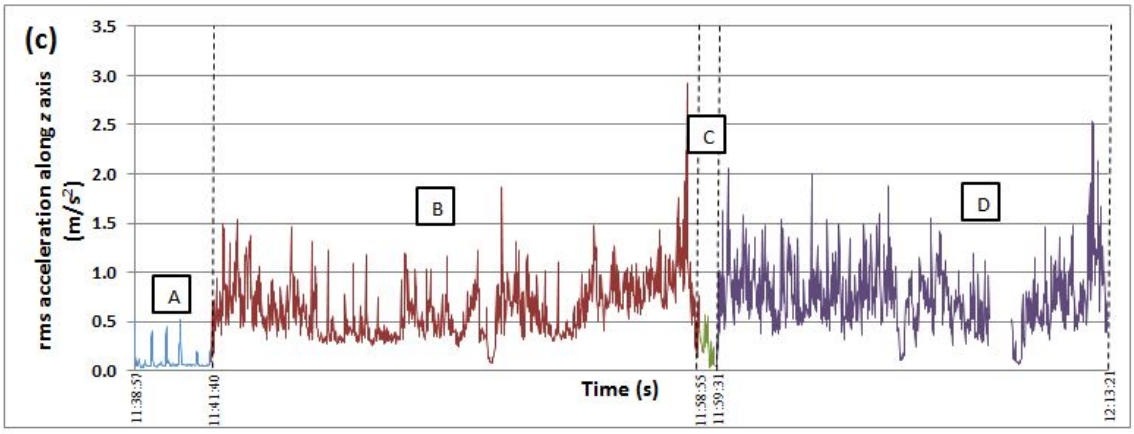


| A | B | C | D |
|---|---|---|---|
| loading | hauling | dumping | return |
| 163 s | 1035 s | 36 s | 830 s |

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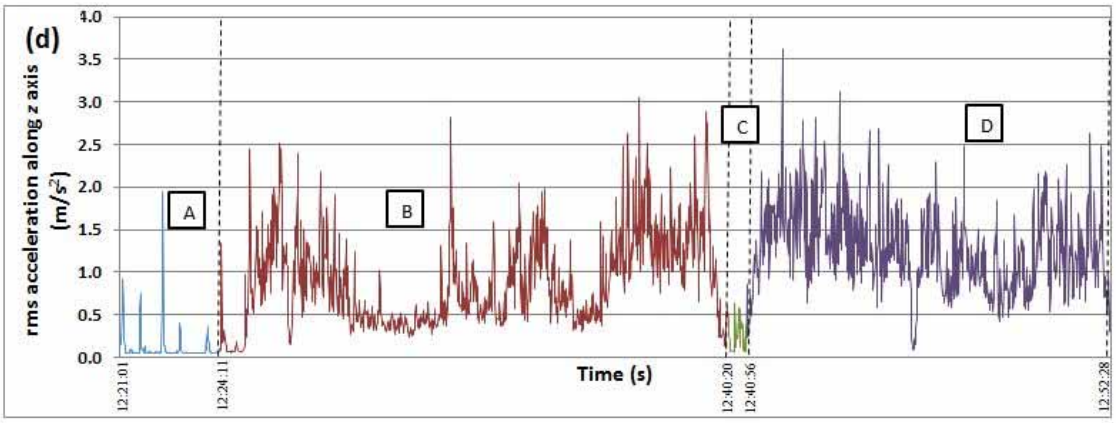


| A | B | C | D |
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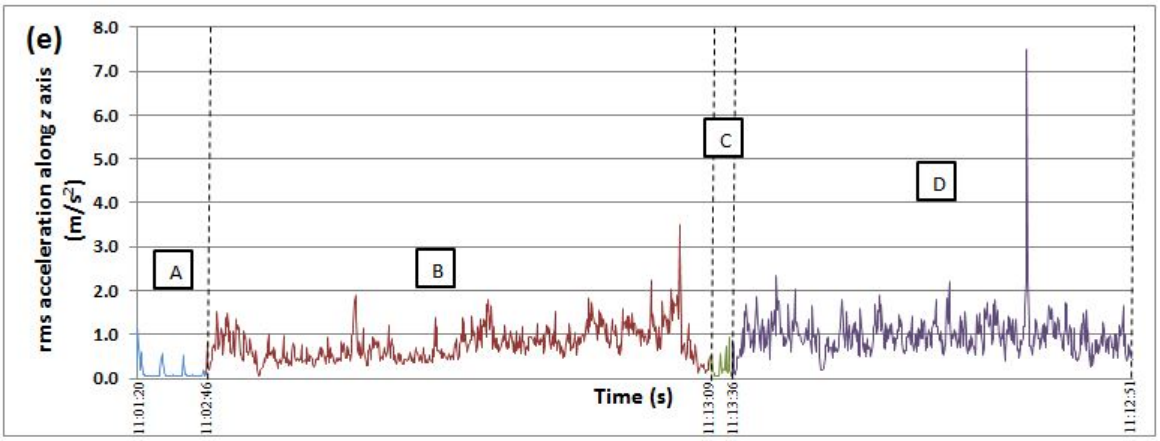


| A | B | C | D |
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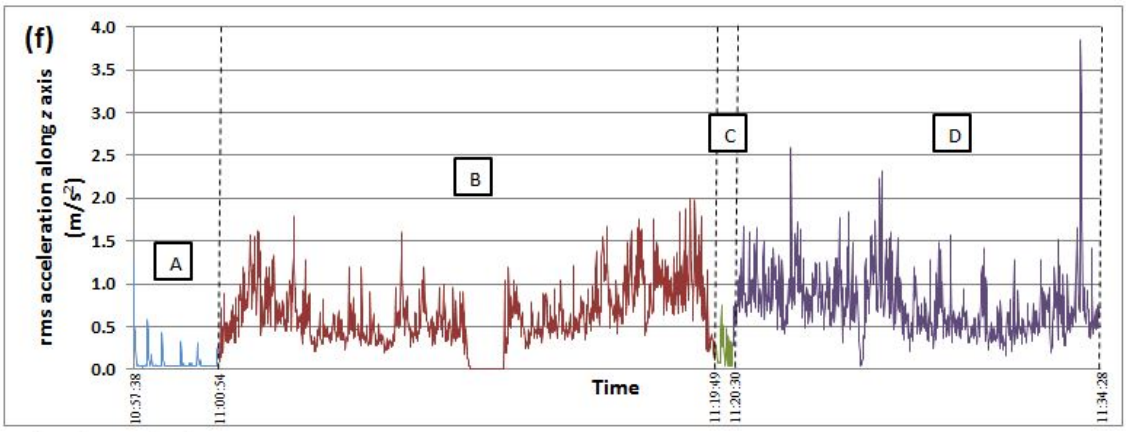


| A | B | C | D |
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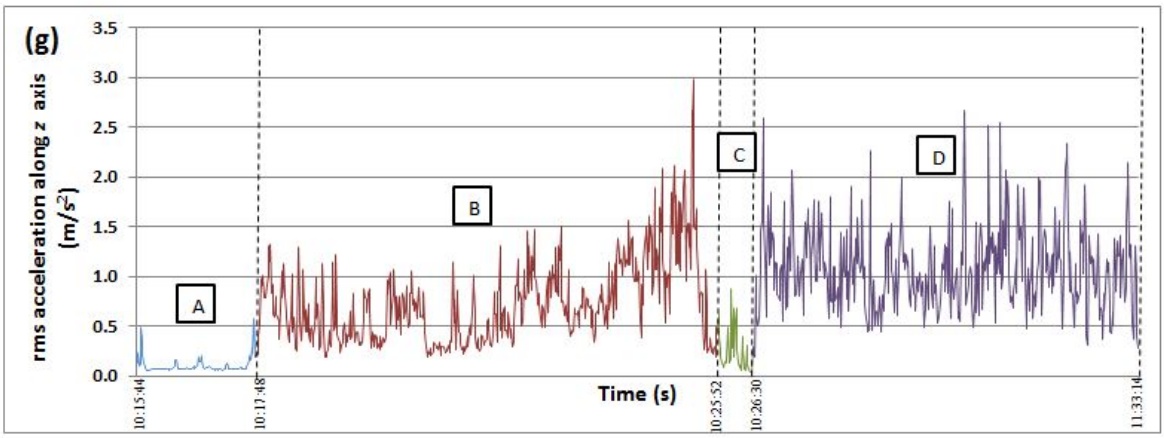


| A | B | C | D |
|---|---|---|---|
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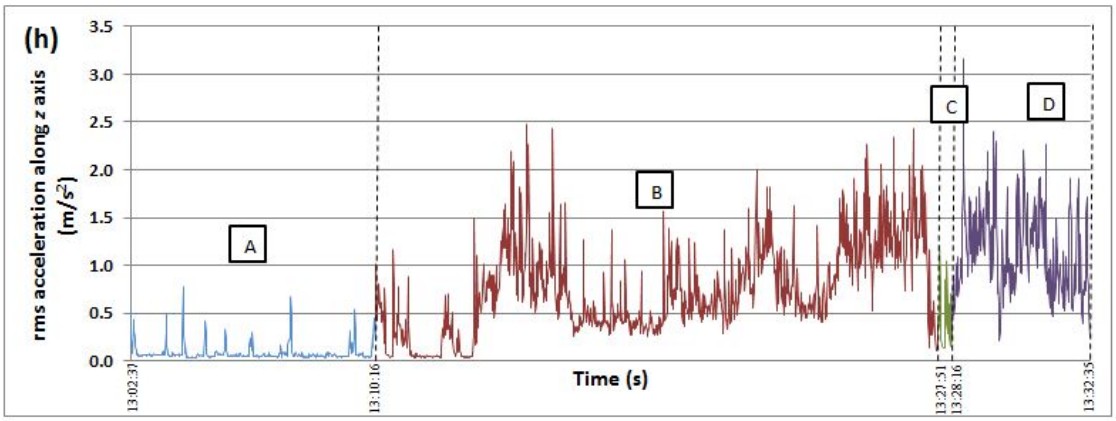


| A | B | C | D |
|---|---|---|---|
| loading | hauling | dumping | return |
| 459 s | 1055 s | 25 s | 259 s |

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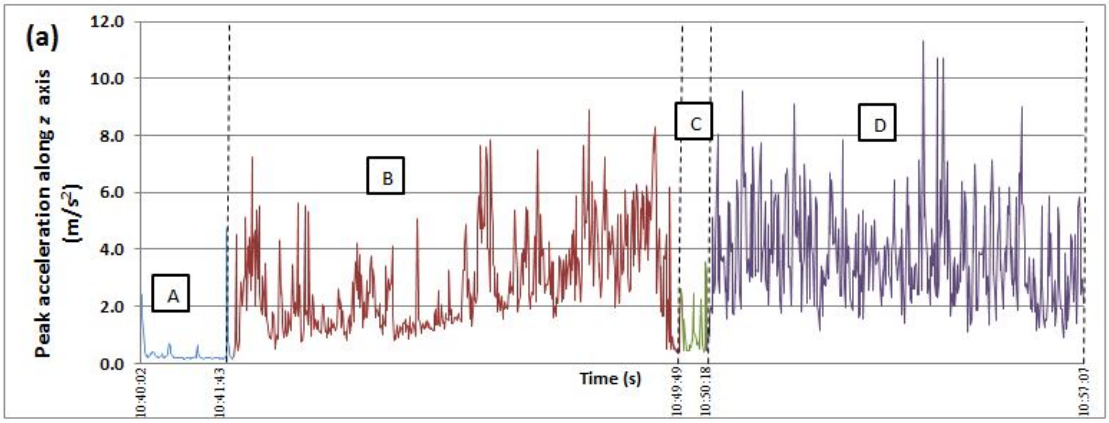


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|---|---|---|---|
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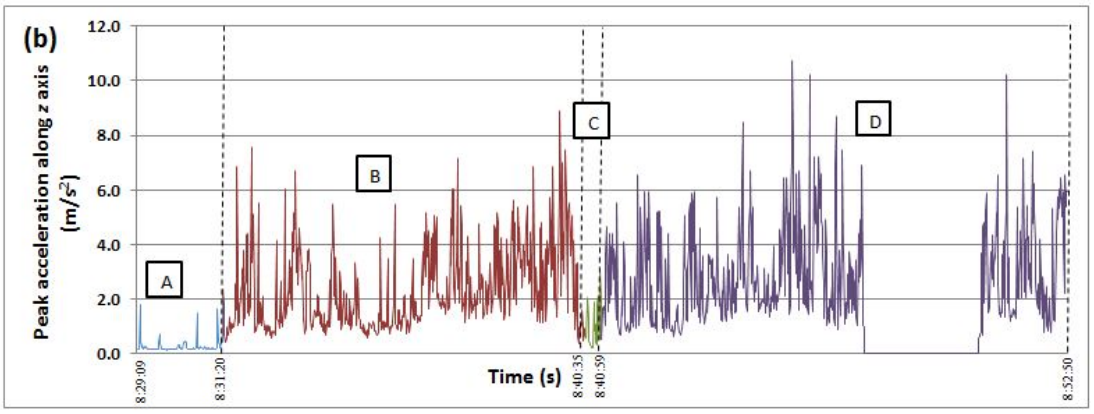


| A | B | C | D |
|---|---|---|---|
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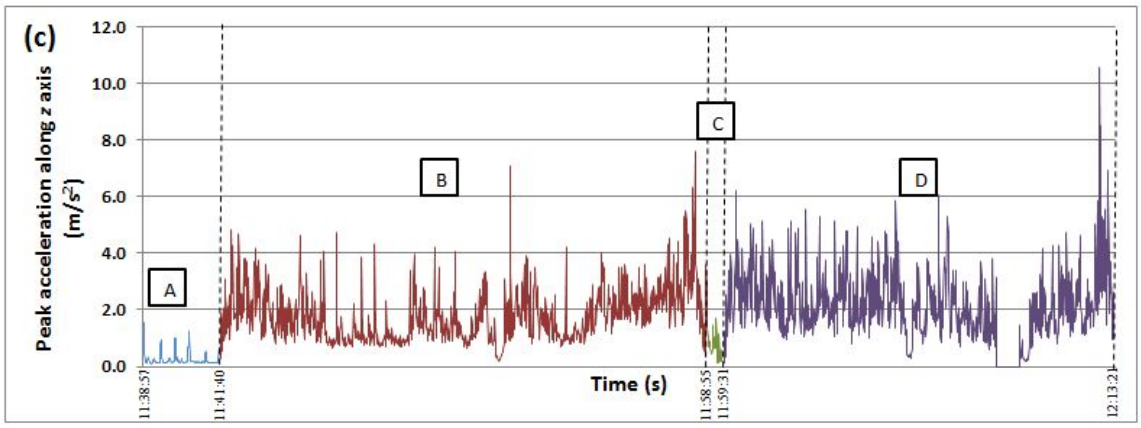


| A | B | C | D |
|---|---|---|---|
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| 163s | 1035 s | 36 s | 830 s |

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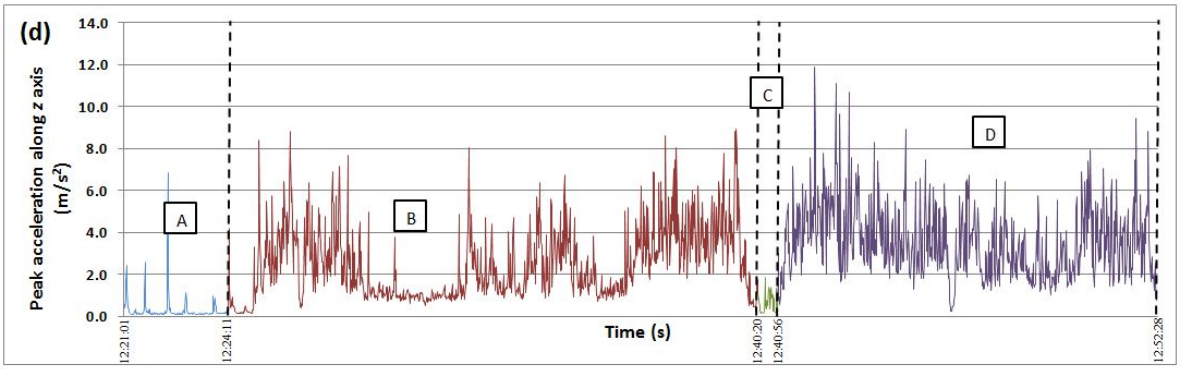


| A | B | C | D |
|---|---|---|---|
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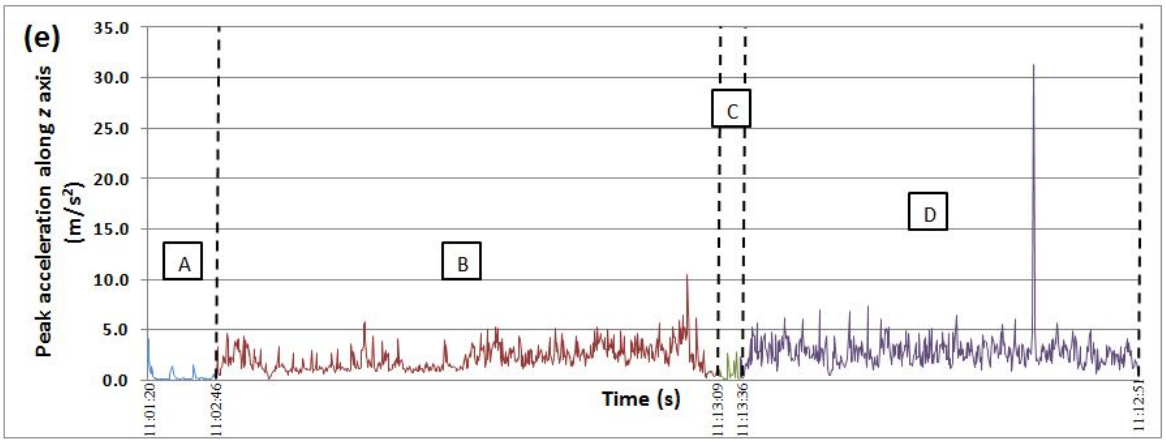


| A | B | C | D |
|---|---|---|---|
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| 86s | 623 s | 27 s | 495 s |

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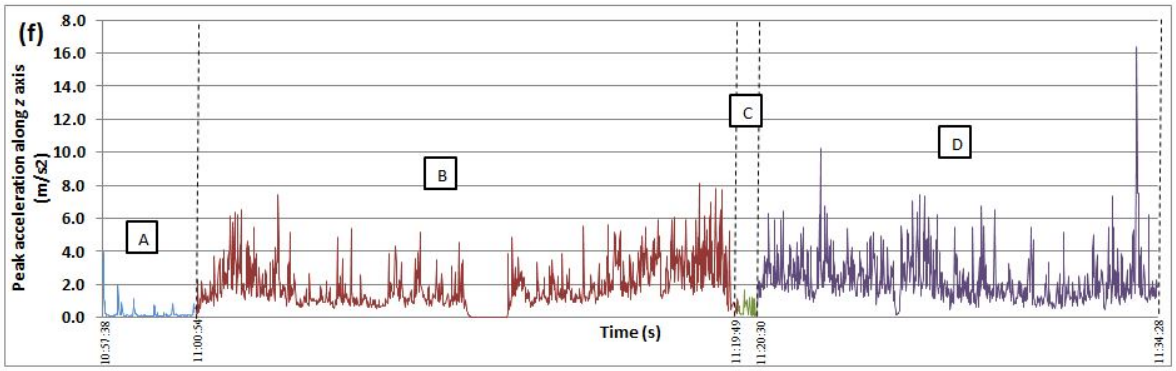


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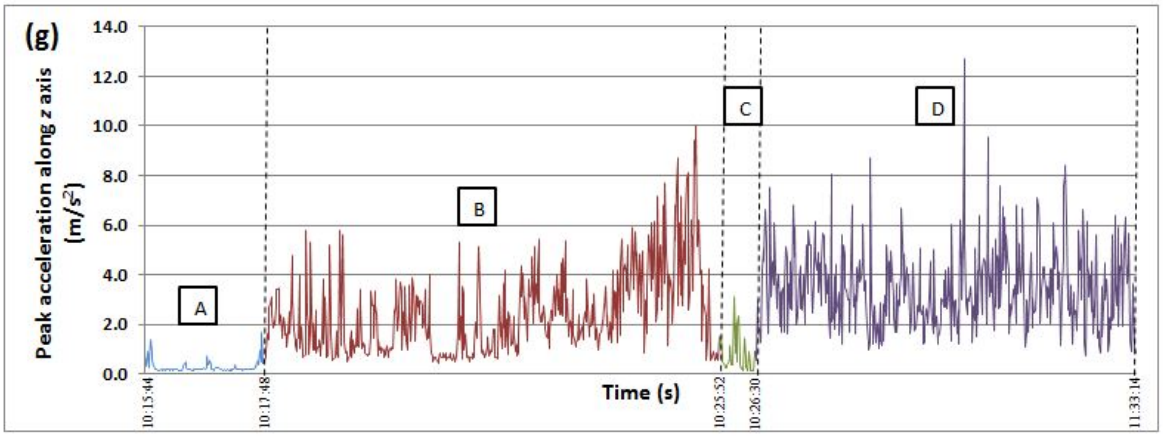


| A | B | C | D |
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| 124s | 484 s | 38 s | 404 s |

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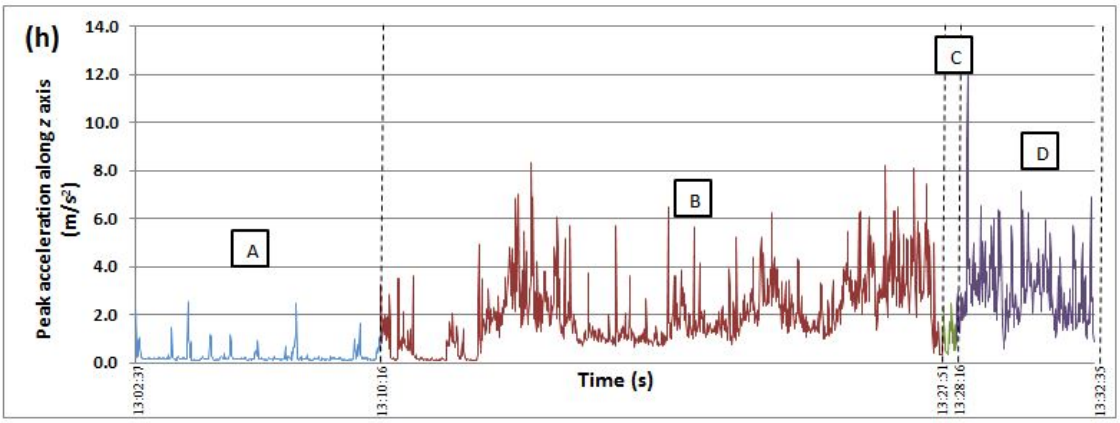


| A | B | C | D |
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| 459s | 1055 s | 25 s | 259 s |

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| Speed of equipment (km/h) | Vibration (z-axis) $ms^{-2}$ |
|---|---|
| 13 | 0.64 |
| 15 | 0.7 |
| 17 | 0.8 |
| 18 | 0.75 |
| 20 | 0.902 |
| 23 | 1.13 |
| 24 | 1.2 |
| 27 | 1.12 |
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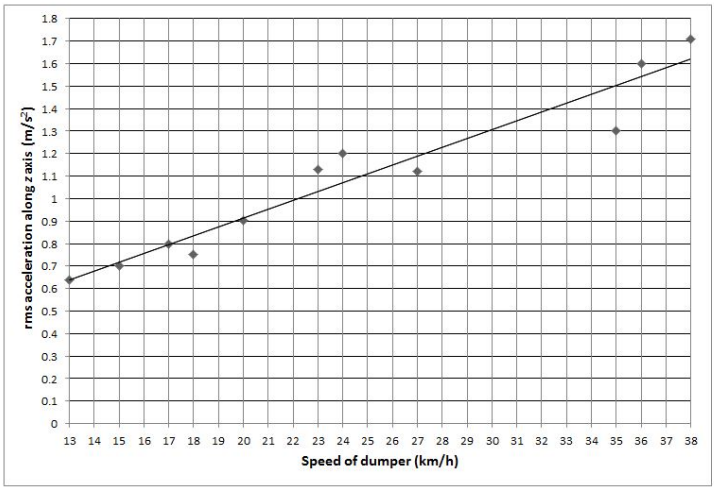


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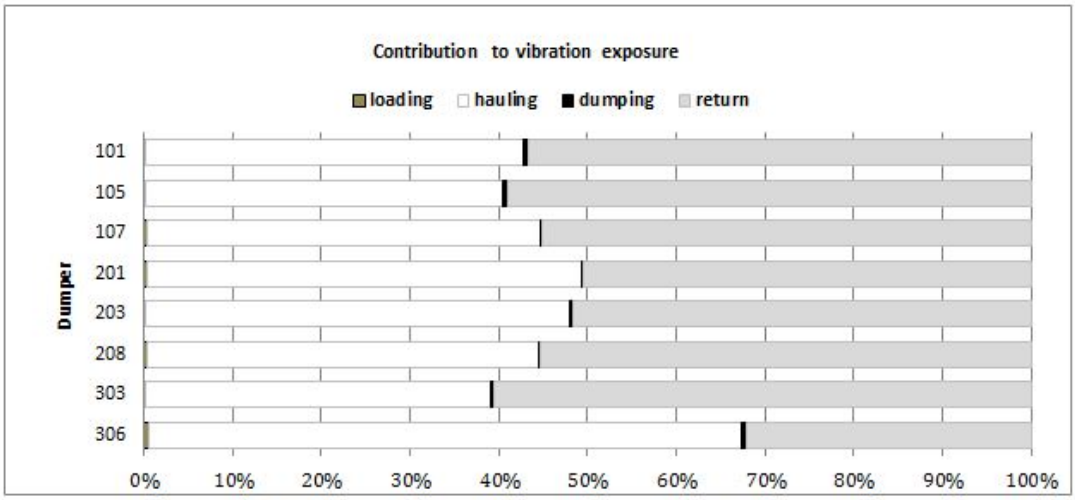


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