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Vibration Effects in Vehicular Road Transportation

C. L. Ranathunga[1], H. H. E. Jayaweera, S. K. K. Suraweera, S. C. Wattage, K. K. D. L. Ruvinda and T. R. Ariyaratne
Centre for Instrument Development, Department of Physics, University of Colombo, Colombo 03, Sri Lanka.

ABSTRACT

This study focuses to certain elements of the Road-Vehicle-Load system which are responsible for the inflicted damage to consignment during road transportation. Bruising injury depends on the energy absorbed by the cargo. Distribution of the power spectral density (PSD) was used as a measure of the vibration energy generated during transportation. “Poor” quality (IRI range 10 to 5) roads induce nearly four times severe damage than that induced by “fair” or “good” quality roads (IRI range 3.5 to 2 or, 2 to 0.9). PSD of the generated vibration is relatively higher in the critical frequency range below 10 Hz. In this frequency range, the rear side of the truck bed indicates nearly a 10 times higher PSD compared to that of the front side of the truck. A higher PSD distribution was also observed at tomatoes occupying higher layer levels in multi-layered tomato columns. Higher PSD levels were observed at very poor quality roads even at lower vehicle speeds. Fair quality roads also produced higher PSD levels, but when travelling at higher speeds. In case of stacked cargo boxes, an increase in PSD level was observed with stack height from the truck bed. Studies performed using the instrumented sphere reveals that, among the positions of multilayered items within the cargo box, the position of the topmost item registered highest PSD level. In addition, the top most item in multilayered cargo packages, has freedom to move and resulting damage can be even higher. The PSD generated by the truck has a good relationship to the quality of the road (judged by a panel in terms of PSR or IRI) and the speed of the truck.

1. INTRODUCTION

Severe ill effects have been observed in transportation of delicate items such as eggs, pottery, fruits and vegetables. It is unrealistic to aim at operating a system which results in no damage at all and similarly a system becomes uneconomic if damage levels are too high. Elements of the Road-Vehicle-Load system, seriously contribute towards the resulting damage during road transportation. [1]. Irregularities or unevenness of the road such as potholes, bumps and kerbs produce harmful impulsive shocks against the consignment. Subsequent acceleration levels are responsible of the resulting damage to the same. The vibration component of the vehicle with the largest effect during transportation is the vertical vibration because the vibration component in the vertical direction is greater than the others [2]. Horizontal accelerations become significant in locomotive transportation, especially when rail wagons undergo shunting operations [1]. In road transportation, the vertical vibration accelerations first felt by the tires of the vehicle are transmitted to the consignment through the truck wheels, suspension system, chassis and the truck bed. Quality of the road is quantitatively evaluated using many methods under the topic road roughness. Road roughness is generally defined as an expression of irregularities in the road surface that adversely affect the ride quality of a vehicle (and thus the user and the load) [3]. Visually but effectively the roads can be

[1] *Permanent address: Department of Physics, University of Sri Jayawardhanapura, Nugegoda, Sri Lanka*

categorized as highways, arterial roads, secondary roads, tertiary roads and laterite roads (rutted, pothole filled lanes on hardened clay) [4].

The stiffness viscous damping coefficients and coulomb friction terms of the suspension system of the vehicle are critical factors in absorbing the vibration energy. During the travel, part of the vibration energy is dissipated mainly into heat within the tires and suspension system. The higher the fraction of energy dissipated within suspension system, the lower is the available energy for bruising the fruit load or damaging the cargo and hence, the lower is the resulting damage. The air pressure of the inflated tires and the suspension characteristics of the vehicle therefore become critical factors in this regard. The harder the stiffness and damping characteristics, more severe is the damage [5]. The gross vehicle weight rating (GVWR) is the mass of the vehicle with driver, passengers, fuel, spare wheel and cargo. The curb weight is the mass of the vehicle alone which is ready for drive with all necessary fittings according to the manufacturer's original specifications [6]. For any vehicle, the manufacturer assigns a recommended upper limit for the payload. The higher the ratio sprung mass to un-sprung mass, the lower is the vertical acceleration felt at the consignment [1]. Estimation of the distribution of the power spectral density (PSD) at the truck bed and different positions of the cargo helps controlling and minimization of the vibration induced damage to the cargo. PSD shows the strength of the variations (of energy) as a function of frequency. The objective of this study is to analyze the parameters that govern the vibration effects in road transportation – particularly tomato transportation – in Sri Lanka.

2. MATERIALS AND METHOD

2.1 Vibration Sensor

A tri-axial Steval LIS302DL MEMS (Microelectromechanical systems) accelerometer coupled to microcontroller is used as the acceleration sensor. The data acquisition system is configured in such a way that its dynamic range is ± 2 g and sampling rate is 100 Hz. There are three axes defined for the accelerometers, but in this application, accelerometers are mounted in arbitrary direction and acceleration along vertical direction is calculated with the data acquired while the system remains stationary. From the stationary data obtained for all three axes of the accelerometer A_x, A_y and A_z, directional cosines were calculated for the gravity. Also, the value $\sqrt{A_x^{\ 2} + A_y^{\ 2} + A_z^{\ 2}}$ was considered as one gravitational unit (1 g). Then the analysis of the dynamic situation was done upon calibrating axes using directional cosines and magnitudes using the calculated 1 g value.

2.2 Road-Vehicle-Load

2.2.1 Evaluation of the Road

The road transportation tests were carried out along a 68 km road from Illukkumbura to Dambulla. Every 1 km segment was evaluated using the Present Serviceability Rating (PSR). PSR, which is based on individual observation, is defined as "the judgment of an observer as to the current ability of a pavement to serve the traffic it is meant to serve".

This subjective scale (Table 1) ranges from 5 (excellent), to 0 (essentially impassable). Since PSR is based on passenger interpretations of ride quality, it generally reflects road roughness because roughness largely determines ride quality. PSR was then converted into equivalent International Road Roughness Index (IRI) using the correlation proposed by Al-Omari & Darter in 1992 [3].

$$PSR - 5 * e^{-0.26(IRI)} \qquad \text{------------ (1)}$$

Table 1: Scale for present serviceability rating (PSR) and approximate international road roughness index of a road

PSR	Quality of Road	IRI
< 1	Very poor	> 6.0
1 to 2	Poor	6.0 to 3.5
2 to 3	Fair	3.5 to 2.0
3 to 4	Good	2.0 to 0.9
4 to 5	Very good	0.9 to 0

The IRI is based on the average rectified slope which is a filtered ratio of a standard vehicle's accumulated suspension motion (mm) divided by the distance travelled by the vehicle during the measurement. The commonly recommended units are m/km or mm/m. The IRI is used to define a characteristic of the longitudinal profile of a travelled wheel track and constitutes a standardized roughness measurement [3].
The PSR of each 1 km segment of the total road was determined by a panel consisting of 04 judges. PSR value was then converted into equivalent IRI using Al-Omari & Darter equation.

2.2.2. Vehicle

A Mitsubishi Canter FE535B6R model truck was used for the study.
Wheel base :- 2,500 mm; Tire size 700 16 LT
Air pressure :- Front 65 psi (4.57 kgf/cm^2); Rear (inner) 55 psi (3.87 kgf/cm^2); Rear (outer) 65 psi (4.57 kgf/cm^2)
Suspension :- Front - parabolic springs and shock absorbers.
Rear - leaf springs, shock absorber and helper spring
Curb weight of the truck (with two side trays) :- 2,225 kg
Gross vehicle weight rating (GVWR) :- 5,500 kg
Maximum recommended payload allowance :- 3,275 kg

2.2.3. Load

The truck was completely loaded with 128 tomato boxes (0.48 x 0.21 x 0.28 m). Loading pattern is shown in the Figure 1. The total payload was about 3250 kg. Cargo has nearly reached the upper limit of the allowable payload.

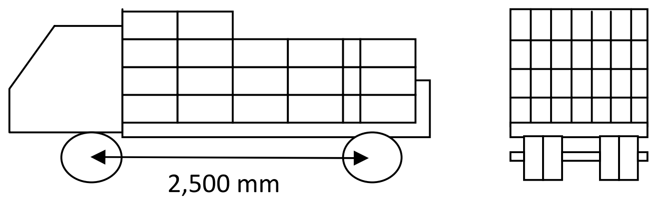


Figure 1: Pattern of the stacking of the tomato boxes on the truck

2.3 Tools for Vibration Measurement

The accelerometers firmly mounted on timber and perspex boards (referred to as "board") were used for the measurement of vibration effects horizontally along the truck-bed and vertically across the cargo (tomato) boxes. These boards, can readily be attached to the truck bed or the timber box using screws, bolts or magic tape. An instrumented sphere was designed and fabricated by embedding an accelerometer within a solid rigiform ball of the diameter of an average tomato. When the size and other physical parameters selected appropriately, the instrumented sphere (referred to as "ball") acts as an individual cargo item (an artificial tomato) within the bulk bin. It helps studying the vibration atmosphere around specific locations in bulk cargo (tomato) boxes by transmitting the digital signal carrying vibration acceleration data in its surrounding. Use of instrumented spere for exploring such vibration environments has now become a common practice [7-9].

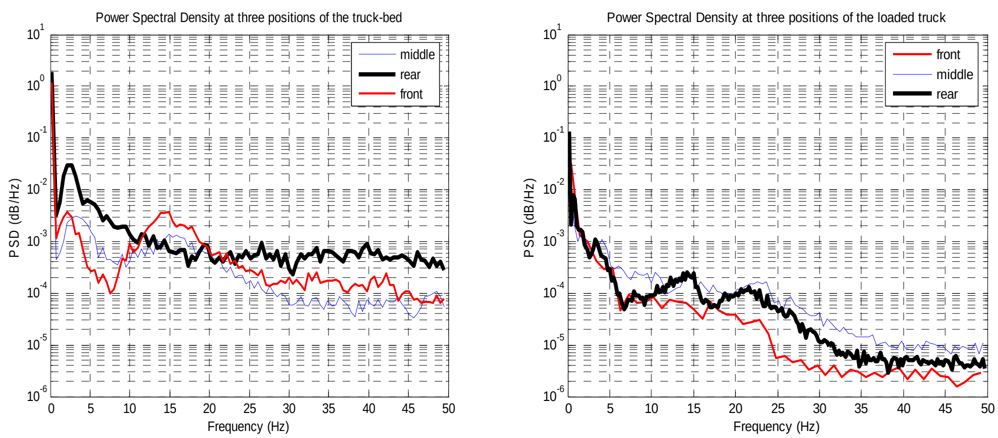
During the laboratory vibration simulation tests and the actual road transportation tests, vibration data were collected at a rate of 100 Hz. Measuring time was about 180 to 300 seconds. The data stored in computer were then analyzed using mathematical software. Welch method was used for estimating the PSD.
Road quality in terms of PSR was determined independently by four judges.

2.4 Distribution of the PSD along truck-bed (horizontally) and across stacks and layers (vertically) of cargo

Power spectral density (PSD; Welch method) was used to study the relative variation of energy at critical frequencies at the desired locations of the empty and loaded truck bed and across stacked cargo (tomato boxes). Based on the assumption that the behaviour of a tomato fruit within a bulk tomato box can be modeled as a single column, the results of a bulk bin with reduced dimensions can be generalized to a full size bulk bin [10]. Columns made of PVC pipes (Ǿ =8.5 cm, height 30 cm) were used for stacking single tomato columns which can hold maximum of five fruits (layers) vertically on one another. The fabricated instrumented sphere was the vibration sensor used within single tomato columns.

3. RESULTS AND DISCUSSION

The distribution of the vibration acceleration at the front, middle and rear positions along the lengthwise symmetry axis of the empty truck bed when the truck was moving at a speed of 20 kmh^{-1} is shown in the Figure 2(a). The variation of the PSD level at front, middle and rear positions of the truck bed which is heavily (99% of rated maximum payload), loaded with cargo - tomato boxes is given in Figure 2(b). Figures show that the power spectral density (PSD) of the vibrations generated by the truck bed is high at frequencies below the 10 Hz, in both the empty and loaded truck. In this critical frequency region, the rear side produces nearly 8 to 10 times higher vibration energy compared to the middle and front sides of the empty truck. For the heavily loaded truck, as a whole, PSD levels or vibration energy at all three corresponding positions was considerably lower. The rear side of the heavily loaded truck produced only up to 2.5 times higher PSD compared to the middle and front side. The relatively lower level of PSD at the front side is attributed to the efficient damping action of the spring-dashpot type shock absorption mechanics attached to the front suspension system. The detrimental PSD level at the rear side of the empty truck dropped down by



(a) (b)

Figure 2 PSD of front, middle and rear positions of (a) Empty Truck Bed (b) Loaded Truck bed

nearly 30 times when the truck was heavily loaded. During the transportation of the tomato load (3,250 kg) from Rathkinda to Dambulla, visual information on the quality of the road was recorded on the scale given in 2.2.1 and the International Road Roughness Index (IRI) was evaluated using the equation 1. The variation of the IRI of the road, speed of the truck, the corresponding variation of the PSD as measured with instrumented sphere ("ball") and the accelerometer attached to the tomato box ("board") are shown in Figure 3. As expected, the PSD of the vibration generated by the truck bed closely follows the variation of the IRI value of the road. Approximately the first 20 km of the total journey of 68 km, was a poor quality road (IRI ranging from 10 to 5). Even at lower speeds (restricted by bumps, potholes and kerbs), the vibration energy generated in this region was relatively higher. It was nearly a 4 times higher energy compared to that experienced at "fair" (IRI 3.5 to 2) or "good" (IRI 2 to 0.9) quality road. Generated vibration energy was relatively higher on poor quality roads and, at higher speeds. PSD measured with accelerometer fixed to tomato box ("board") and instrumented sphere ("ball") produced similar results. Furthermore, results obtained with instrumented sphere reveal its freedom to vibrate at higher acceleration levels.

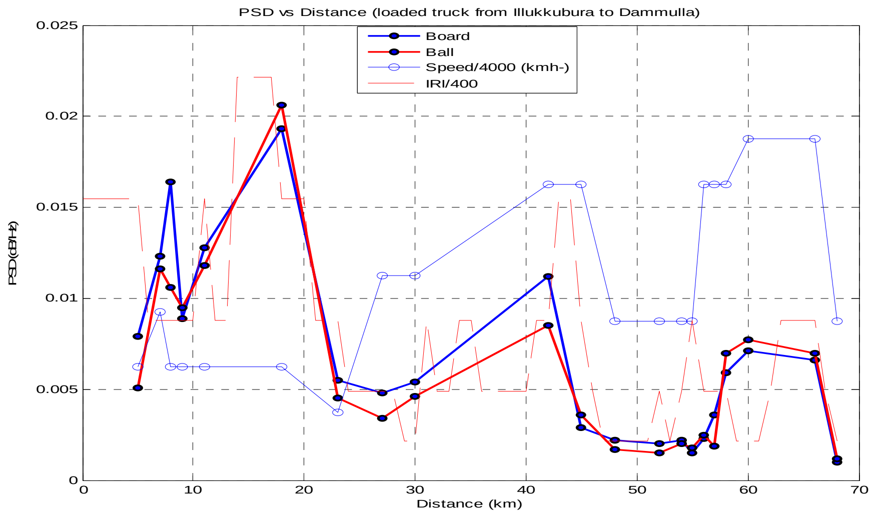


Figure 3 Road quality, speed of the truck and the road-induced vibration energy in terms of power spectral density observed at various parts of the road during tomato transportation from Illukkumbura to Dambulla.

The transmission of the vibration acceleration through tomato boxes stacked on the moving truck was simulated with four single tomato columns (labeled 1S to 4S) stacked on a laboratory vibration simulator (Figure 4). Each column contained five tomato

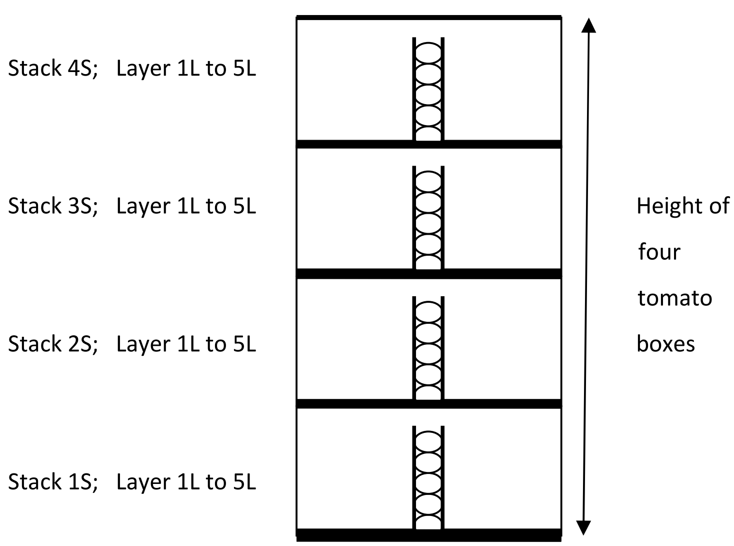


Figure 4. Schematic diagram of tomato columns mounted on vibration simulator; Four stacked single columns from 1S to 4S each containing five layers 1L to 5L of tomatoes

layers (labeled 1L to 5L). Vibrator simulates acceleration nearly 10 times as powerful as that produced by the transport truck under poor road conditions. Such a powerful vibration was used to inflict a substantial damage to tomatoes in a short time. The "ball" was placed in between tomatoes for making vibration measurements. A comparison of the PSD observed at a frequency of 7 Hz at different stack and layer levels, is illustrated in Figure 5. It indicates a very close behaviour that has been reported by the previous investigators [2, 11] i.e., the higher the stack or layer number, the higher is the transmitted vibration acceleration. Topmost tomato in a column experienced the highest acceleration in particular column and hence, a much severe damage is expected.

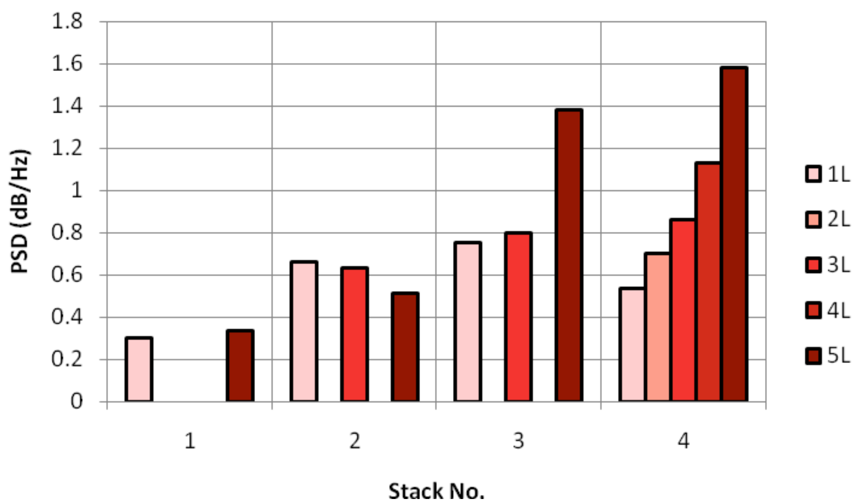


Figure 5. Distribution of the power spectral density over the five tomato layers in four columns stacked on one another.

4. CONCLUSIONS

In the course of transportation, heavily loaded truck (high ratio sprung mass to unsprung mass) induces less vertical acceleration and hence, generates less vibration energy. Often, the actual load was closer to (or sometimes even higher than) the recommended maximum payload capacity of the vehicle. Though it has detrimental effects on the whole vehicle (chassis, suspension, axels, wheels and tires), the damage inflicted on tomatoes is minimal compared to lightly loaded truck. Vertical acceleration in the frequency range below 10 Hz was found to be high compared to other frequency regions and according to the literature it is the critical region which causes most of the damage to tomatoes. The vibration acceleration experienced in the frequency range above 10 Hz, which is characteristic to steel spring trucks, is associated with less energy and does relatively little damage to the cargo (fruit). Rear of the truck produces almost 10 times higher PSD compared to that of the front of the empty truck bed.

Under simulated vertical vibration, an amplification of the PSD was observed with stacked tomato columns and also at higher tomato layers within a particular column in this critical frequency range. The topmost tomato in every column experiences the highest acceleration in that column and, is at the risk of greater damage. If the vertical acceleration in real road transportation exceeds 1 g, then a soft padding material on top of the topmost tomato layer would avoid the cyclic impacts.

The level of PSD generated at a certain road segment has a very close relationship with the road quality judged by a panel in terms of PSR or IRI. Poor road conditions produce higher PSD imparting severe damage to tomatoes even at lower speeds. From the results above it can be concluded that the topmost layer tomatoes at the topmost tomato box stacked at the rear side of the truck bed is severely damaged. Damage would be even severe at poor quality roads.

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