INFLUENCE OF ROAD ROUGHNESS ON THE TRANSPORTATION OF FRESH PRODUCE

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ABSTRACT

The agricultural sector is one of the largest economic sectors in South Africa. Damage to fresh produce during transportation and handling decreases the value of the products of this sector and it increases logistics costs. Bad road conditions cause more damage to produce and it increases the maintenance cost of vehicles used to transport produce from growers to distributors. Perishable commodities such as fruits and vegetables are sensitive to a variety of factors including temperature, atmospheric gasses and vibrations induced during transportation. All of these factors affect the quality of the fresh produce that reaches the consumer.

This paper focuses on damage to fresh produce caused as a result of exposure to different vibrations during transportation. As the riding quality of roads deteriorates more vibrations are experienced and the possibility of damage to produce is increased. Vibrations induced during transportation of produce on different road conditions are evaluated. It is expected that more vibrations would be induced on gravel roads than national and provincial roads in the Limpopo province of South Africa.

1 INTRODUCTION

Agriculture is one of the largest economic sectors in South Africa. Damage to products within this sector does not influence the cultivator alone, but can have a major impact on the economy of the country. In 2007 the South African Institute of Civil Engineers (SAICE) stated that 72 per cent of the national road network is approaching the end of their design life (Service-publication, 2008). The South African Road Federation (SARF) has expressed concern about the poor road condition of the country's provincial and municipal road networks (Service-publication, 2008). The lack of funding and expertise in municipalities throughout the country is resulting in a backlog of maintenance actions. Figure 1 shows the condition of poorly maintained gravel roads in Limpopo.

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Figure 1: Condition of Rural roads in the Limpopo province.

Trucks travel on a variety of roads within the transportation network. In most cases, the first stage of travel is via a gravel road. Gravel roads have a higher roughness than national and provincial roads (Jarimopas et al, 2005). The roughness of the pavement brings about a vertical acceleration in the vehicle. In turn, the vehicle exerts a force on the pavement which causes the pavement to deteriorate (Steyn and Monismith, 2010). The way in which the pavement responds depends on a number of factors including:

- The speed of the vehicle;
- The dynamic tyre load, and
- The strength of the pavement.

Due to repeated cycles of loading associated with heavy vehicles, the road surface deforms and the profile of the road changes. If the road is not maintained the unevenness of the road surface leads to an increase in dynamic tyre load. Overall, the pavement deteriorates faster than expected (Steyn and Monismith, 2010).

Numerous factors including handling and distribution as well as climatic and physical changes after harvesting influence the quality of fresh products. Vibrations generated by Vehicle-Pavement Interaction (V-PI) are one of the major factors that cause damage. The objective of this paper is to quantify the vibrations a truck and the produce it carries have to endure due to different road conditions when travelling from growers in the Limpopo Province to market distributors in Pretoria and Johannesburg.

The extent of this study was limited to damage caused by transportation. Damage that resulted from postharvest handling was not considered. It is, however, important to recognise that these damages do exist. The paper focuses on the measurement of vibrations at different positions on the truck and different vertical positions within the palletised container. Different road conditions were also considered. The effect of temperature and the maturity of the fruit were not explicitly considered.

2 DETAILS ON SPECIFIC CONCEPTS

2.1 Vehicle-Pavement Interaction (V-PI)

V-PI can be defined as "the system in which the vehicle and the pavement exert mutual forces on each other". This system should be able to describe the vehicle and the pavement and their components as well as the way in which these components influence each other (Steyn and Monismith, 2010).

2.2 Vibrations associated with V-PI as a result of different road conditions

A relationship exists between road conditions and vibrations experienced by a truck and its cargo. As road conditions deteriorate, damage to cargo that is sensitive to different vibration ranges, will increase (Steyn, 2010). Three major frequencies can be identified when analysing road conditions (Jarimopas et al, 2005). These are:

- 0.1 to 5 Hz. This range represents the body bounce of the truck;
- 5 to 20 Hz. This range represents the axle hop response, and
- > 20 Hz. This is the response from the structure, road roughness and drive train.

In the frequency range of 0.1 to 5 Hz all the roads analysed showed the highest Power Spectral Density (PSD) levels. The PSD is "A mathematical transform which computes the amplitudes of the sinusoids that could be added together to construct the profile. It is called a Fourier Transform. The Fourier Transform can be scaled such that it shows how the variance of the profile is 'spread out' over a set of sinusoids. When scaled in this manner, the transform is called a Power Spectral Density function." (Sayers and Karamihas, 1998). For gravel roads the PSD values of 0.1 to 5 Hz are significantly higher than for the other road surfaces. Jarimopas et al. (2005) concluded that the most damage to cargo, especially fresh produce, would occur on unsurfaced roads at high speeds.

2.3 Effects of inadequate road maintenance

Studies have shown that maintenance costs of vehicles increase as the quality of the road deteriorates (Steyn, 2010). The condition of a road is expressed in terms of the International Roughness Index (IRI). The IRI is a scale that gives an indication of the unevenness of a road profile. The scale ranges from 0 mm/m to 16 mm/m, 0 mm/m being a smooth road and 16 mm/m being an impassable road (Sayers et al, 1986). An increase in road roughness leads to an increase in the dynamic effects that are experienced by a vehicle. This increase translates into a higher than average dynamic tyre load. Higher tyre loads may be similar to overloading. Therefore the road deteriorates earlier than it would have done if it was maintained properly (Steyn, 2010).

2.4 Vibrations generated at different positions on the truck

Fresh produce are transported using a wide variety of trucks. There are three types of trucks that are predominantly being used for freight transportation in South Africa. These vehicles are two-axle rigid trucks, articulated trucks with a tandem drive axles and interlinks with seven axles (Steyn and Monismith, 2010). Hinsch et al. (1993) analysed steel-spring and air-ride suspensions during refrigerated truck transport. Vibrations were measured with accelerometers at the rear and the centre of the trailers. They indicated that the highest Root Mean Square Vertical Acceleration (RMSVA) levels, which give an indication of the amount of energy that needs to be dissipated by the truck-cargo combination, are found at the rear, regardless of the suspension type and the commodity that was transported. Accelerations at the centre of the trailers of the steel-spring and air-raid suspensions were 36 per cent and 59 per cent respectively of the accelerations measured at the rear.

2.5 Losses suffered due to cargo damage

Chonhenchob et al. (2009) monitored the shipment of four different products in Thailand, which included cabbage, lettuce, pears and plums. Cuts and bruises with the following dimensions were identified:

- Bruises that measured more than 1 cm^2, and
- Cuts more than 1 cm long and a minimum of 5 mm deep.

Cuts and bruises with these dimensions are known to decrease the retail price of fresh produce (Chonhenchob et al, 2009). All the produce that was examined indicated that the most damage occurred on the roads at the packaging houses and the least amount of damage at the retailers. Roads from the farms to the packaging houses were gravel roads. These road conditions accounted for the highest losses. Roads from the packaging houses to the distribution centres were single carriageway asphalt roads and road from the distribution centres to retailers were well maintained asphalt roads.

3. EXPERIMENTAL METHODS

Accelerometers were placed at four different locations on the left-hand side of the truck. Position no. 1 was chosen because it is the furthest away from the truck's centre of gravity, therefore the vibrations generated at this position were higher than at other locations. Position no. 2 and no. 3 were above the axles of the trailers and position no. 1 was on the drive axle. Figure 2 indicates the positions of the accelerometers.

Figure 2: Position of accelerometers on trucks.

Accelerometers were positioned at the front and middle of the truck as well as the top, middle and bottom within the palletised containers. Because stacked packaging does not respond to impact as a single body, a variation in vibrations was observed at different positions on the truck and within the stack. The pallets should however behave as a unit to a certain extent since they are tightly wrapped in plastic.

The roughness of the road (in terms of IRI) was determined by placing accelerometers on a test vehicle and driving the truck route at a constant speed. The same test vehicle was used to drive on sections for which the IRI values were known. The accelerations measured on the truck route were converted to the IRI value with a model developed by Tsalamandris (2011).

4 RESULTS / DISCUSSION

4.1 IRI values for different road sections

The different road sections for which the IRI values were determined were the N1 between Pretoria and the Kranskop toll plaza, the R33 to Nylstroom (Modimolle) and from Nylstroom halfway to Vaalwater, and the Driefontein gravel road. The average IRI values calculated for these road sections are presented in Table 1. This data show that the national and provincial roads are in a good condition and that maintenance done on the gravel road is inadequate.

Table 1: Average IRI values for different road sections along truck route.

Road section	IRI [mm/m]	Condition
National	0.79	Good
Provincial	2.54	Good
Gravel	8.06	Poor

4.2 Dominant frequencies

Resonance frequencies for different types of fresh produce, calculated by O’Brien et al. (1965) and Van Zeebroeck et al. (2006) were compared with the frequencies measured during transportation. O’Brien et al. (1965) and Van Zeebroeck et al. (2006) measured the elasticity of fruit and converted it to resonance frequency using a mathematical model. Due to time constraints the experiment for calculating resonance frequencies was not repeated.

A histogram analysis, comparing the resonance frequencies from the literature (O’Brien et al. (1965); Van Zeebroeck et al. (2006)), with the dominant frequencies measured on the trucks was conducted. Figure 3 provides a visual representation of the two histograms created for the dominant frequencies and the damage frequency range of the different fruits. The shaded area in Figure 3 represents the overlap of dominant frequencies with the frequency range where different types of fruit are likely to be damaged. This overlap is an indication that some of the frequencies experienced during transportation may result in produce damage. At this stage the severity of the damage cannot be quantified.

4.3 Accelerations under different conditions

Each of the positions indicated in Figure 2 experienced different accelerations due to V-PI. For different types of trucks these accelerations at the same position on the vehicle are different and dependent upon a variety of factors such as tyre pressure, suspension type and the size of the vehicle. To evaluate the effect of different road conditions on a truck and the cargo it carries, acceleration distributions were determined for different trucks.

4.4 Full truck versus empty truck

Two different trucks were evaluated; a rigid truck with a trailer and an interlink truck. Accelerations were measured for a full and empty load. Data sets for a full and empty load were available for the rear axis on the rigid truck but not for the trailer. For the interlink truck both data sets were available at all four positions on the vehicle.

The interlink truck showed a large variance in vibration distributions for a full and empty load. The largest variance between full and empty loads was measured at the front of the truck. These results are presented in Figure 4. The rigid vehicle showed little variance between a full and empty load.

Similar distributions for all four positions on the interlink truck were observed when the truck was empty. These distributions are showed in Figure 5.

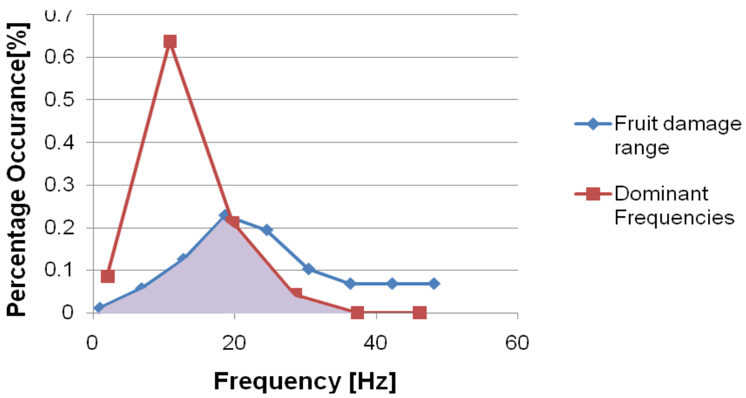

Figure 3: Comparison between dominant frequencies from the analysed data and the vibration range which results in damage as identified from the O'Brien et al. (1965) and Van Zeebroeck et al. (2006).

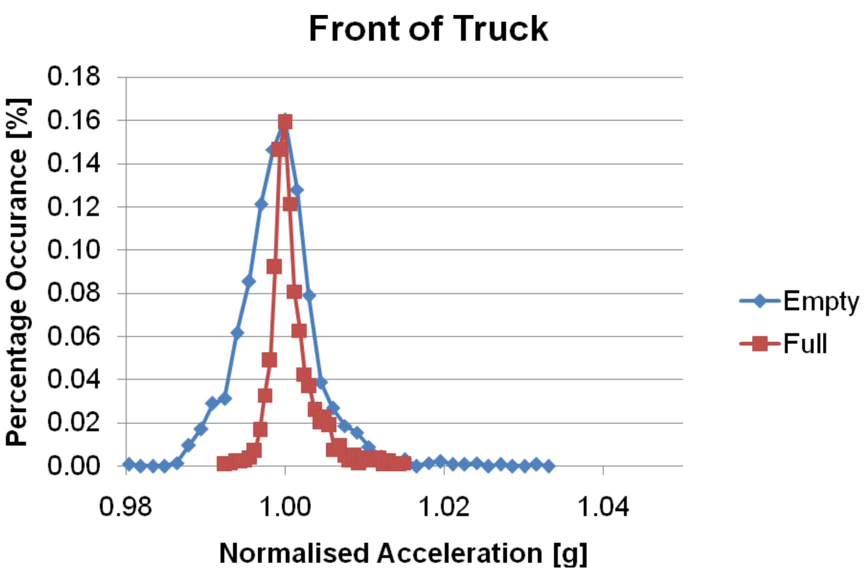

Figure 4: Distribution of accelerations at the front for a full and empty loaded interlink truck.

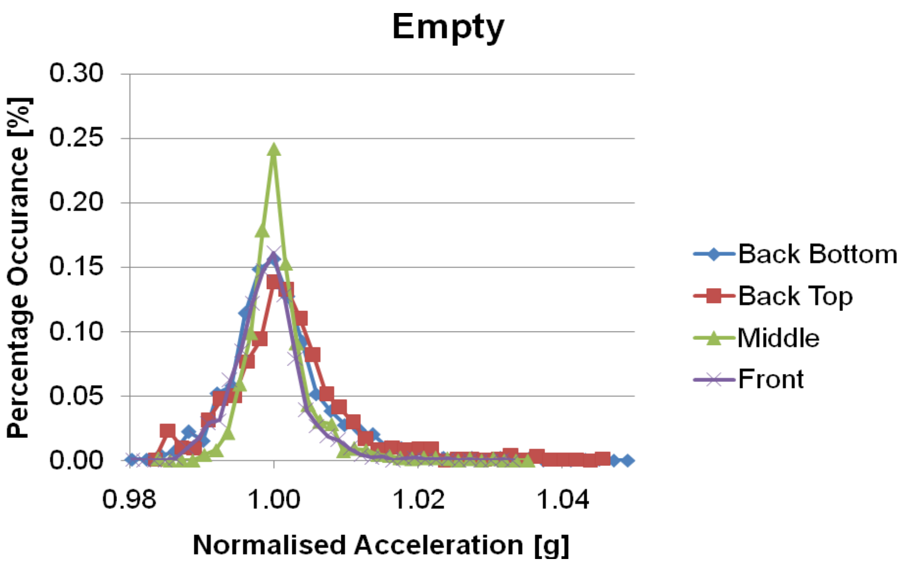

Figure 5: Acceleration distributions for different positions on an interlink truck with no load.

From Figure 6 it can be seen that a wider distribution of accelerations was measured at the back positions on the truck than on the front and middle positions for a full load.

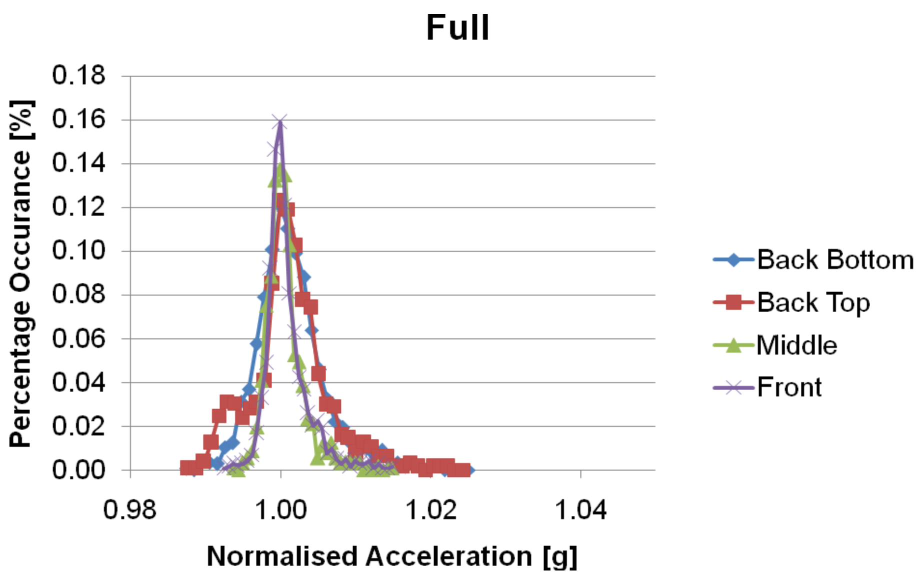

Figure 6: Acceleration distributions for different positions on an interlink truck with a full load.

For a full and empty truck the position of the centre of gravity moves relative to the position where the load is placed. Because the interlink is a larger vehicle than the rigid truck the position of the centre of gravity can change significantly from when the truck is empty to when it is full. The centre of gravity influences the accelerations measured at different positions on a vehicle. As stated by Steyn and Monismith (2010), a point on the vehicle further away from the centre of gravity would experience more vibrations than a point closer to the centre of gravity. Therefore, more accelerations were measured at the back position on the interlink truck than the middle and front for both cases.

It was not possible to compare the full and empty distributions of the interlink truck with the rigid vehicle since clear data sets for the rigid vehicle were not available at all positions.

4.5 Effect of packaging

To measure the escalating or damping effect that packaging has on accelerations, accelerometers were installed at different vertical position within the palletised containers. This was done for fibreboard boxes on the rigid vehicle. It was not possible to compare the performance of similar or different packaging on different vehicles because only one data set was available. However, it is possible to compare accelerations within the packaging with accelerations measured on the truck.

The acceleration distributions to which the accelerations, measured on the packaging, will be compared are shown in Figure 7. For the rigid truck higher accelerations were experienced at the back. The truck was not loaded to maximum capacity and most of the containers were placed in the front and middle of the truck. No information for packaging at the back of the truck is available and therefore no conclusion in terms of this position can be made. The results are not invalidated by the lack of data because overall accelerations within the packaging can be compared to accelerations measured on the truck to see if packaging dampens or escalates the effects of V-PI.

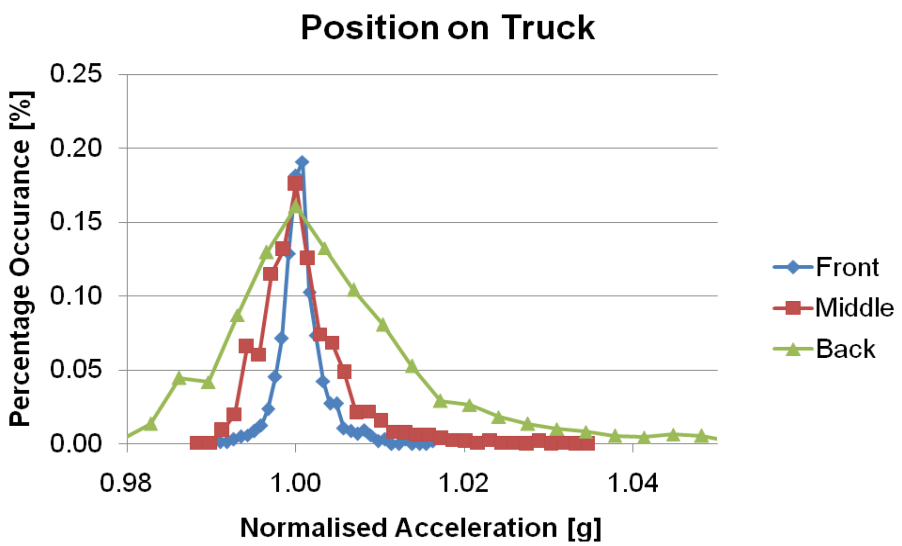

Figure 7: Acceleration distributions for different positions on the rigid vehicle.

For both the middle and front positions on the truck the top boxes experienced higher accelerations than the middle and bottom boxes within each stack. When these acceleration distributions are compared to the acceleration distributions measured on the truck, the packaging at the bottom and the middle of the stack has the same distribution than the distribution of accelerations measured on the truck itself. The top boxes experienced higher accelerations than the truck.

Produce at the bottom and in the middle positions are better protected against vibration damage than the produce in the top packaging. These results are confirmed by previous studies done by O'Brien et al (1965), Jarimopas et al (2005), and Berardinelli et al (2004).

Figure 8 show the comparison for packaging in the middle at the front and middle of the rigid vehicle. Packaging at the front of the truck experienced fewer vibrations than those in the middle of the truck. The same conclusion was made when the top position was compared for the middle and front of the truck. There were no results for the bottom packages in the middle and therefore no conclusion could be made. The results are not invalidated by the lack of data because overall accelerations within the packaging can be compared to accelerations measured on the truck to see if packaging dampens or escalates the effects of V-PI.

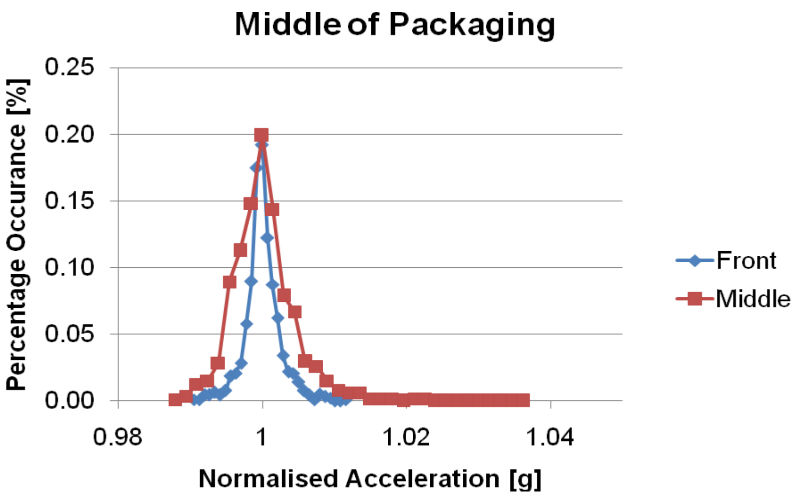

Figure 8: Acceleration distribution for packaging in the middle of the stack.

Further comparisons between vibrations of the packaging and the truck indicate that the packaging in the middle and bottom positions of the pallet does not amplify or reduce accelerations generated by V-PI. The packages at the top of the pallets were not a part of the unit and therefore less energy was required for it to accelerate.

4.6 Effect of different road conditions

To compare the effect of different road conditions on the truck and the packaging three different road sections were analysed. These sections included a well maintained national road, a provincial road and a gravel road.

The widest distribution of accelerations for the middle of the truck is experienced when travelling on a gravel road. The provincial and national roads showed narrower distributions. For the front position the acceleration distributions of the national, provincial and gravel roads were similar to the distributions for the middle position.

When the acceleration distributions for different road conditions on the palletised containers were evaluated, results were similar to the results for the rigid truck at the front and middle positions. The gravel road had the widest distribution followed by the provincial and lastly the national roads. Figure 9 shows the distribution for accelerations of containers in the front of the truck at the bottom of the stack of containers. When compared to the other data it can also be seen that the containers at the top of the stack of fibreboard boxes experienced more accelerations than boxes at other positions.

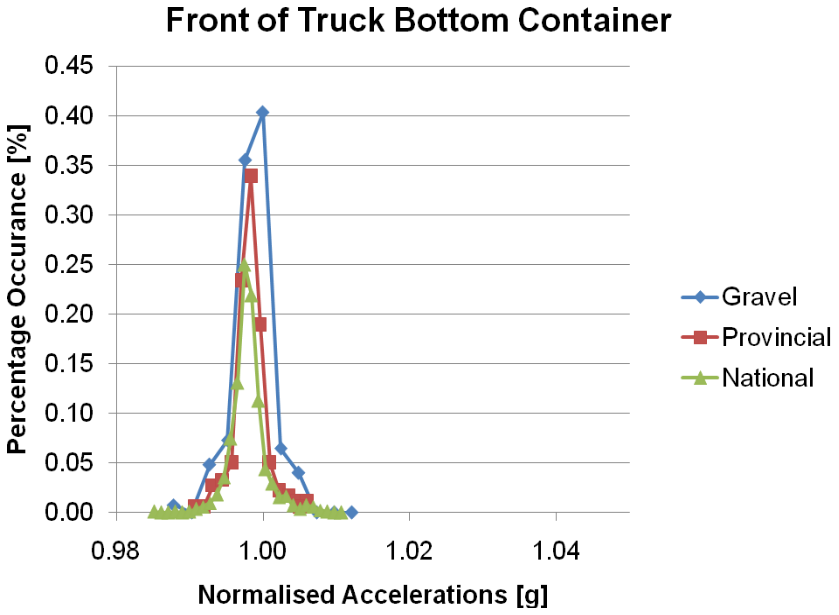

Figure 9: Acceleration distributions for different road conditions experienced by the bottom containers at the front of the truck.

4.7 Energy absorbed by the system

The energy that was absorbed by the rigid truck and the packaging on the truck is presented in Figure 10. The back position of the truck absorbed the highest amount of energy for all road conditions. The energy absorbed by the packaging at the front position of the truck decreases from the top to the bottom. The packaging in the middle of the truck shows the same pattern although no information for the bottom packages is available.

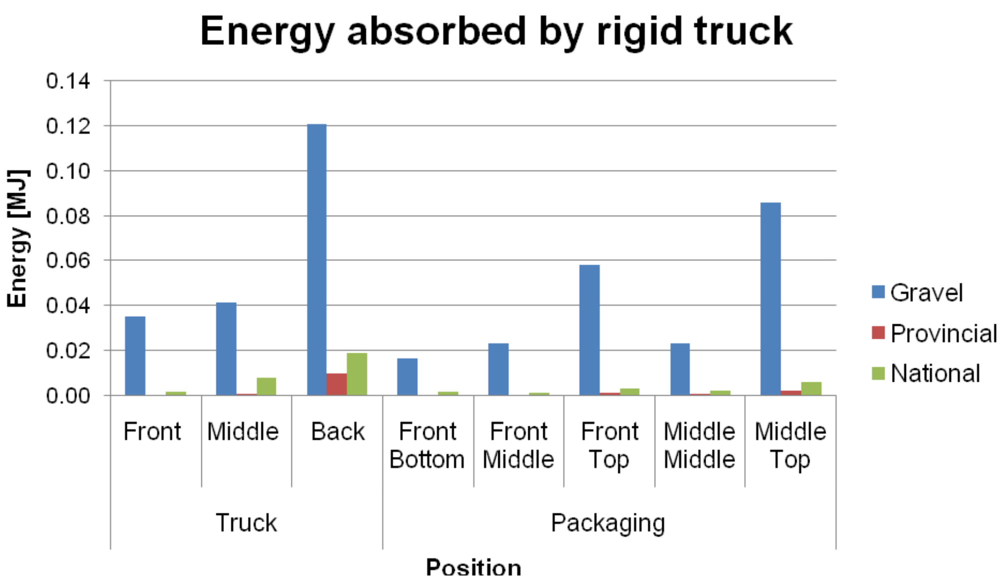

Figure 10: Energy absorbed by a rigid truck and the cargo on the truck.

The energy absorbed when travelling on the gravel road is the highest for all the analysed positions. It was expected that more energy would be absorbed by the system when travelling on the provincial road than on the national road. This was not the case and it may be a result of the different speeds that the truck travelled at whilst on the different roads. Further studies should be done to confirm this hypothesis.

The section of gravel road that the truck travels is 40 times shorter than the section of national road. More damage is done when travelling on a small portion of gravel road than when travelling on a long section of the national highway, which is well maintained.

4. CONCLUSION AND RECOMMENDATIONS

From the results it can be concluded that the gravel roads in this study have higher IRI values than the national and provincial roads. If these IRI values are compared to the IRI values in the study by Steyn and Bean (2010) it can be seen that maintenance costs on vehicles which travel on these roads would be exceptionally higher than for other road conditions. Since farmers in the Limpopo Province are constantly exposed to these conditions, maintenance costs and losses due to vibration damage would lower their profit margin.

Insufficient maintenance of gravel roads leads to higher IRI values. As the roughness of a road increases more vibrations are generated on vehicles that travel on these roads. From the data presented in this paper it can be seen that the energy absorbed by the rigid vehicle is the highest when travelling on gravel roads. A higher energy input means that more energy needs to be dissipated during the journey from growers to distributors. This could result in an increase in damages to produce.

The different positions on a truck do not experience the same vibrations. The point furthest away from the centre of gravity experienced the most vibrations. On a truck the position of the centre of gravity may vary with different load conditions. In most cases the point furthest away from the centre of gravity is the top back position of the truck. For both trucks that were analysed the widest acceleration distribution was at the back of the truck. Produce positioned at the back would present the most vibration damage at the end of a journey (Jarimopas et al, 2005).

The position of a package relative to other packages and the truck influences the amount of vibrations that a particular package experiences. In most cases packages are palletised to reduce the time it takes to load and unload them from the truck. This is also done to ensure that they do not move during transportation. Packages at the bottom and middle of the palletised container experience fewer vibrations than packages that are at the top of the pallet. This is because less energy is required to move the top packages than the bottom ones. The bottom and middle packages are held in position by the packages above them and the plastic wrapping, whereas the top packages are held in position only by the wrapping.

One of the main reasons for packaging fresh produce before loading onto trucks for transportation is to protect it from possible damage. The packaging on the rigid vehicle experienced the same vibrations as the truck for the middle and bottom positions. The top packaging however, experienced more vibrations than the truck. No results were available for different packaging and therefore no conclusion can be made in terms of which packaging provides the most protection.

A comparison between dominant frequencies identified in the study, and the different ranges of vibrations to which produce are sensitive indicated that there is an overlap in frequencies. This may be problematic since the chance of damage is increased if frequencies generated by V-PI fall within the resonance frequency range of the particular produce that is transported.
With this study it is now possible to quantify the amount of the vibrations for different road conditions and compare them with each other.

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