Quality deterioration and loss of shelf life as a result of poor road conditions

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Abstract: Postharvest science focuses mainly on the quality of fresh produce. One of the areas of interest is the shipment of tomatoes using road transport. Because tomatoes have a limited shelf life, it is vital to control the factors that lead to early deterioration of the quality of the product. Logistical operations can cause numerous forms of cuts and bruises on harvested tomatoes which compromise their quality and appearance. For this experiment, the in-transit conditions were monitored on trucks shipping tomatoes from three farms in Limpopo, South Africa to the fresh produce market in Pietermaritzburg. This research attempts to create a model that relates tomato damage and loss in shelf life to the road condition, fruit ripeness and position in the container. With this information in hand, logistic planners can make informed decisions during route planning. Transportation cost can be weighed against the cost of losses of produce during transportation. Similar models can be developed to include other types of fruits and vegetables.

Keywords: tomatoes; postharvest losses; riding quality; accelerometers; shelf life.

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1 Introduction

One of the main purposes of most commercial businesses is to maximise income. Agricultural businesses, including the commercial farming of tomatoes, function in the same manner. Because tomatoes have a limited shelf life, it is vital to control the factors that lead to early deterioration of the quality of the product. Logistical operations can cause numerous forms of cuts and bruises on harvested tomatoes which compromise their appeal and reduce the economic value to the grower and retailer (Chonhenchob et al., 2009).

1.1 Tomato quality and shelf life

Tomatoes rank under the top consumed vegetable crops in the world (Willcox et al., 2003). Unfortunately, a considerable amount of freshly harvested tomatoes never reaches the consumer due to bruising during transportation and handling.

When considering the quality of fresh tomatoes, consumers are primarily concerned with the firmness and the appearance of the product which includes the colour and freedom from imperfections (Kasmire and Kader, 1978). Tomato quality also reduces as the tomato ripens during its shelf life.

The shelf life of a product can be defined as the time period during which food maintains its quality and consumption safety under reasonable anticipated distribution, storage and use conditions (FSAI, 2014).

Several authors (Boyer and McKinney, 2013; Nasrin et al., 2008; Kader et al., 1978) investigated the various treatments and packaging that can be used to increase tomato shelf life. The conclusion was that pink tomatoes (tomatoes of breaker stage ripeness) can be stored for up to ten days before changing to red ripe and notably deteriorating without special packaging or chemical treatment.

Because tomatoes are a non-homogeneous fruit with locules and cross-walls, the potential for mechanical damage due to impact loading would differ as the location of impact changes (Li, 2013). Li (2013) indicated that the probability that a tomato would rupture on impact increases by 14.5 times when the tomato is loaded on cross-wall tissue. In terms of bruise development, the impact loading on locular tissue is more harmful (Van Linden et al., 2006). Further studies by Van Linden et al. (2006) and Van Zeebroeck et al. (2007) indicated that the contact time of various levels of impact also contribute to increased bruise development. Bruised tomatoes have a decreased shelf life and an inferior value to consumers. Unfortunately, there is limited information available on tomato bruise identification and how it influences the shelf life.

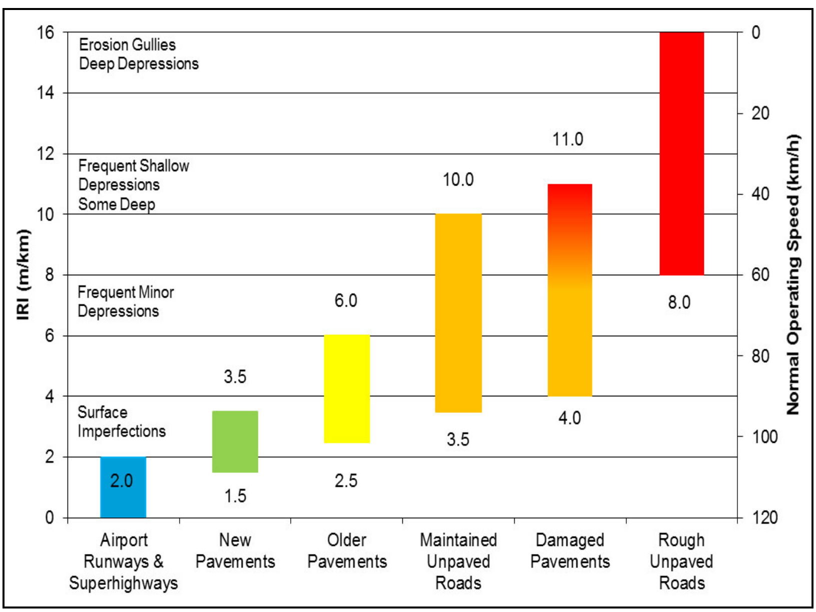
1.2 Vehicle-pavement interaction

Road transport is one of the most efficient ways to move produce from origin to destination because of shorter travel times and the ability to reach more inland destinations than any other mode of transport. Although the flexibility of road transport is an advantage, previous studies have indicated that fruit and vegetables suffer mechanical damage due to in-transit vibrations (Jarimopas et al., 2005). These in-transit vibrations are caused by vehicle-pavement interaction (V-PI), which can be described as a system where the vehicle (and its components) and the pavement (and its components) exert mutual forces on one another. Pavement roughness initiates the vertical acceleration of a vehicle and in return the dynamic response of the vehicle causes pavement distress and deterioration.

Pavement roughness is the expression of irregularities in a pavement surface defined over an interval between two points (Sayers and Karamihas, 1998). Roughness does not only affect the riding quality but also the fuel consumption and vehicle maintenance costs.

To be able to quantify the roughness of the road the International Roughness Index (IRI) was developed. Figure 1 show the IRI scale. On the left side of the graph the IRI index is shown. The x-axis provides a description of the range of IRI values that can be expected for different road conditions. The right side of the graph shows the suggested operating speed. The IRI best satisfy the criteria of being time stable, relevant, transportable and readily measurable (Sayers and Karamihas, 1998).

Figure 1 International roughness index (see online version for colours)



According to Steyn and Bean (2009) there is a strong relationship between road condition and the vibrations that a truck experiences when travelling on a road. This transfer to the transported cargo, and vibration induced damage could be a result of poor road conditions.

Jarimopas et al. (2005) indicated that a higher percentage damage to produce can be expected when travelling on gravel/unsurfaced roads at high speeds. Chonhenchob et al.

(2009) evaluated frequencies generated by trucks for the shipment of fresh produce in Thailand. Roads between the growers and packaging houses were unsurfaced and the vibration levels observed on these roads were significantly higher than for any of the other roads.

Several researchers indicated that there is a difference in vibrations measured at the rear of a truck and in the middle of a truck (Hinsch et al., 1993; Berardinelli et al., 2005; Pretorius and Steyn, 2012). The vibrations measured would also differ depending on the vertical position where accelerations are measured. There are two views regarding the vertical position; the first indicates that the most damage occurs in the top layers of the packages (O'Brien et al., 1963) and the second view indicating that the most damage occurs in the bottom layers of the packages (Schoorl and Holt, 1982).

2 Materials and method

The focus of this paper is on the damage component that road conditions contribute to the quality deterioration of fresh tomatoes. It is expected that roads with higher roughness values could cause premature deterioration in the quality of tomatoes. The in-transit conditions were monitored on trucks travelling from three farms in the Limpopo province of South Africa to the fresh produce market in Pietermaritzburg near the East Coast. These trucks drive on a variety of roads including unsurfaced roads where higher roughness values are probable along with more produce damage. The route travelled is shown in Figure 2.

Figure 2 Road sections travelled during field experiment (see online version for colours)

The experimental setup consisted of two phases. The first phase of the project included the measurement of road roughness, the measurement of vertical accelerations that the system components are exposed to, and the measurement of the in-transit pressures applied to the tomatoes.

Tomatoes of three different ripening stages were considered, mature green (referred to as green tomatoes), breaker stage (referred to as pink tomatoes) and red ripe (referred to as red tomatoes). The cultivar used for the experiment was Nemo Netta.

The equipment used during the field experiment included the following:

- A high-speed laser profilometer for road roughness measurement.
- Gulf Coast Data Concepts X16-1D accelerometers for the measurement of vertical accelerations. This data was also used to determine the amount of energy that the pavement/vehicle/cargo system absorbs.
- Tekscan i-Scan pressure sensors, installed in-between the layers of tomatoes to measure the transit induced pressures.

The second phase of the project involved an experimental setup in the laboratory. A vibration table was used to simulate the in-transit conditions while monitoring the pressures applied to tomatoes. The locations of impact were monitored for colour changes. Different situations were assessed including the effect of the number of layers of tomatoes as well as the tomato ripeness. The equipment used during the laboratory simulation included the following:

- A spectral dynamics medium force vibration system to simulate in-transit vibrations.
- Tekscan i-Scan pressure sensors to measure inter-tomato pressures. These pressures can be related to the in-transit measurements that were collected during the field data collection phase.
- A HunterLab MiniScan spectrometer to measure the colour change at the location of impact on the tomatoes.
- Gulf Coast Data Concepts X16-1D accelerometer to relate the energy that the system absorbs with the in-transit energy measurements.

2.1 Field measurements

2.1.1 Roughness measurements

There were three different road sections that the trucks traversed. These sections are presented in Figure 2. The sections consisted of a gravel/unsurfaced road, the provincial road and the National highway. Road roughness measurements were monitored and collected every 10 m using the PaveProf profilometer.

The maximum speed that trucks are allowed to travel was of 80 km/h. The distance of travel was 1,050 kilometres. Departure times from the packaging house are scheduled for late afternoon and trucks arrive at the market during the early hours of the morning. The vehicles that were used during the experiment are standard interlink (truck-tractor and two semi-trailer combination) fleet trucks.

2.1.2 Acceleration measurements

Accelerometers were installed on the truck and tomato packaging for data collection. There were two different types of packaging that were considered. The first type is a halfbin (Figure 3). This container is mostly used for the shipment of tomatoes between the farms and the central packaging house. A halfbin can have eight to ten layers of tomatoes on top of each other. This package has a weight of about 80 kg.

Figure 3 Installation of accelerometers on halfbins (see online version for colours)

The second packaging type considered was standard boxes (Figure 4) that can hold up to three layers of tomatoes. This package has a weight of approximately 5 kg and is easy to handle.

Figure 4 Installation of accelerometers on small boxes (see online version for colours)

Accelerometer installation is shown in Figure 3 and Figure 4. As a control measure, accelerometers were installed on the body of the truck. The accelerometer frequency measurement was set at 50 Hz.

Each accelerometer has a real-time clock which was synchronised with the clock on the global positioning system (GPS). This information was used to determine the location on the road at which a certain acceleration was measured.

2.1.3 Inter-tomato pressure monitoring

To determine the forces that act on the tomatoes during transportation, pressure sensors were installed in-between the fruit layers. The sensors were set to measure at a frequency of 2 Hz. Sensor installation is shown in Figure 5 and Figure 6.

Figure 5 Installation of pressure sensor in halfbins (see online version for colours)

Figure 6 Installation of pressure sensor in small boxes (see online version for colours)

2.1.4 Selection of road sections

Eighteen road sections, measuring one kilometre in length, were selected for analysis. Selection of road sections was based on average roughness values. The roughness values along with the surface type and the category of road condition are presented in Table 1. A variety of roughness values and surface types were covered. Extreme roughness values were not noted and is not included as part of this study.

Table 1 Road section selection based on roughness

Roughness (IRI) [m/km]	*Surface type*	*Condition*
0.74	Surfaced	Good
1.60	Surfaced	Good
2.21	Surfaced	Good
2.22	Surfaced	Good
2.32	Surfaced	Good
2.46	Surfaced	Good
2.47	Surfaced	Good
2.53	Surfaced	Average
3.14	Gravel	Average
3.18	Surfaced	Average
3.54	Surfaced	Average
4.20	Gravel	Average
4.52	Gravel	Average
4.70	Surfaced	Average
5.16	Gravel	Poor
5.89	Gravel	Poor
6.26	Gravel	Poor
7.09	Gravel	Poor

2.1.5 Frequency and amplitude analysis

For each selected road section, the dominant frequency was determined using the software that accompanied the accelerometer. There were two frequencies identified that were perceived as dominant. These frequencies were 2.5 Hz and 13 Hz. The identified frequencies relate to the vehicle body bounce and axle hop frequencies (Jarimopas et al., 2005).

A fast Fourier transform (FFT) analysis was run to create a power spectral density (PSD) plot. The PSD plot showed the frequency ranges measured by the accelerometers as well as the energy input observed at that frequency. The frequencies were compared with the roughness values. There was no established or perceived relationship between frequency and roughness. Thereafter the power values from the PSD graphs were compared with road roughness and a linear correlation was recognised. Because the size of the containers differs, their response towards vibrations would differ. Two linear relationships were established, one for halfbins and one for boxes. The energy input from the in-transit measures had to be correlated with the laboratory measures.

Energy can be related to amplitude as expressed in the following equation:

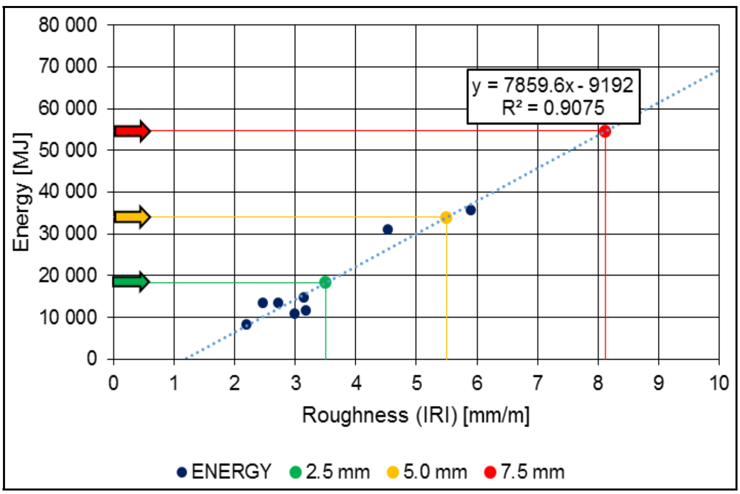
$$E = \frac{1}{2}kx^2 + \frac{1}{2}m(0)^2 = \frac{1}{2}kA^2 \quad (1)$$

The mass (m) (the tomato) is at its maximum displacement at the exact time where the velocity (v) is zero. All the energy would be potential energy and the displacement (x) would be equal to the amplitude (A).

This relationship was used to calculate the energy inputs generated by the amplitudes during the laboratory experiment.

Because of the nature of the experimental setup the energy versus road roughness graph from the small box analysis was used to calculate equivalent road roughness values for the different laboratory amplitudes as shown in Figure 7.

Figure 7 Calculation of roughness values using the total energy (see online version for colours)



The linear relationship for small boxes was selected because the weight of the test containers (filled with tomatoes) corresponds to that of a small box rather than a halfbin. Further evaluation in this regard is recommended.

From amplitudes of 2.5 mm, 5.0 mm and 7.5 mm equal field road roughness values of 3.50 m/km, 5.49 m/km and 8.12 m/km respectively, were determined.

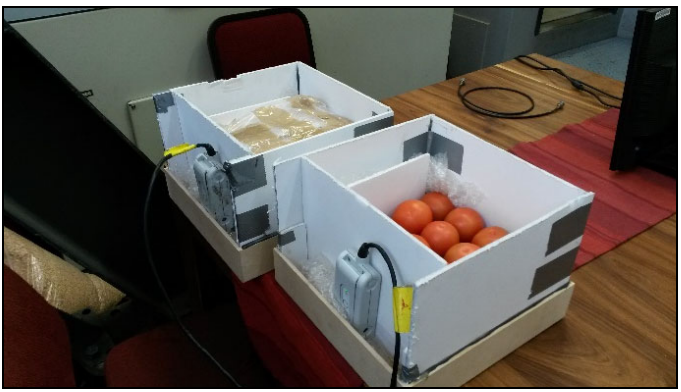
2.2 Laboratory setup

The second phase of the experiment consisted of laboratory work. The frequencies at which testing had to be conducted was determined from field experiment accelerometer analysis. To ensure that the tomatoes for laboratory testing do not get damaged during transportation, layers of bubble wrap were placed in-between the tomatoes. When transporting tomatoes to the laboratory it is impossible to eliminate tomato damage in total therefore each tomato was inspected for damage prior to testing.

2.2.1 Installation of pressure sensors

To simulate the in-transit conditions of the boxes and halfbins three experimental containers holding two, four and six layers of tomatoes were tested. Only 32 tomatoes were used per box as the bottom two layers. For the boxes containing the four and six layers a rubber mat was placed on the second layer and sand bags with the weight of four and two layers were positioned respectively on top of the rubber mat. The mass of the sand was determined by weighing randomly selected tomatoes and taking the average. The 16 tomatoes weighed in total between 1.5 kg and 1.8 kg. An average of 1.7 kg was used for every additional layer to be added on top of the two layers of tomatoes. The pressure sensors were installed between the bottom two layers. The experimental setup is shown in Figure 8.

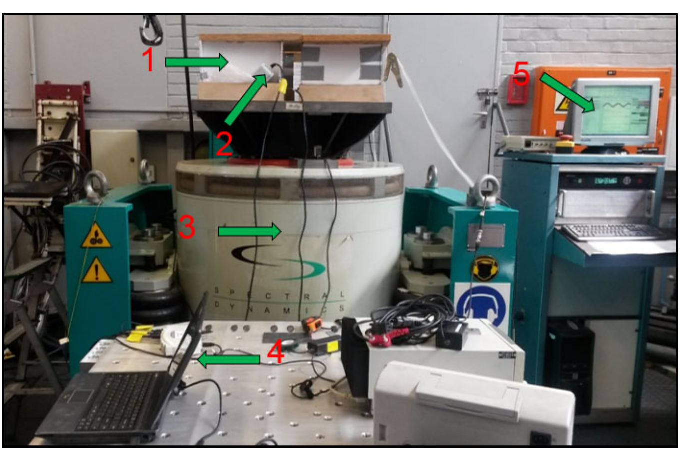
Figure 8 Boxes with the two and four-layer setups (see online version for colours)



2.2.2 Vibration table setup

The frequency that was selected for testing was 13 Hz (vehicle axle hop). The experimental setup is shown in Figure 9.

Figure 9 Vibration table experimental setup (see online version for colours)



The three boxes (1) with the two, four and six layers were placed on top of the vibration table (3) and were fixed with ratchet cables that would ensure that the boxes do not move around. Fixing the boxes allowed the experimental setup the mimic palletisation of boxes of tomatoes. The pressure sensors (2) were connected to the computer (4) and the frequency of data collection was set at 2 Hz. This frequency was selected to ensure that the data is comparable to field data. The frequency, amplitude and time settings for the vibration table (5) were adjusted for the requirements of each experiment. Three amplitudes were selected, 2.5 mm, 5.0 mm and 7.5 mm. After every experiment four tomatoes were selected for colour and condition monitoring.

A total of 81 tests were conducted. Table 2 show the different test setups. For each ripening stage of the Nemo Netta tomatoes, a total of 27 tests were completed.

Table 2 Summary of tests that were conducted

Amplitude (mm)	*Green*			*Pink*			*Red*		
	Time (sec)			*Time (sec)*			*Time (sec)*		
	60	*600*	*6,000*	*60*	*600*	*6,000*	*60*	*600*	*6,000*
2.5		2 layers			2 layers			2 layers	
5									
7.5									
2.5		4 layers			4 layers			4 layers	
5									
7.5									
2.5		6 layers			6 layers			6 layers	
5									
7.5									

2.2.3 Colour measurements

The purpose of the colour and condition monitoring process was to determine the marketability and shelf life of the tomatoes. There are only three methods for consumers to assess whether they would be willing to purchase tomatoes from a retail shelf. These include the physical appearance as well as the firmness of the tomatoes and the presence of soft spots.

Four to five control tomatoes were selected to monitor colour change in undamaged tomatoes. All the experimental tomatoes were kept at a temperature of 18°C. Tomato colour was monitored for up to ten days using the HunterLab MiniScan colour metre.

2.2.4 Consumer perspective

For calibration purposes a binary matrix was constructed by asking the question: ‘Would you purchase this tomato if it was on the retail shelf?’ For a ‘yes’ answer the number ‘0’ was allocated to the reading. If the answer is ‘no’ the number ‘1’ was allocated. It was assumed that tomatoes have a shelf life of ten days. The loss of shelf life was calculated from the matrix.

From each of the experimental setups, three tomatoes were selected for monitoring. These were the same tomatoes used for the colour measurements. Eight to eleven people were asked to give their opinion about the tomatoes and whether they would purchase it. If more than five individuals indicated that the tomato would not be purchased after each day of monitoring, it was the end of shelf life for that tomato.

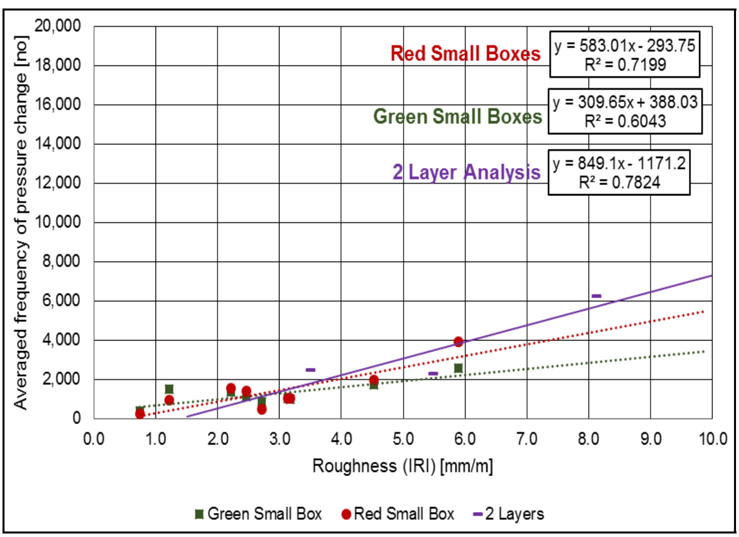
3 Results

3.1 Pressure analysis

The pressure that tomatoes are exposed to had to be determined form the in-transit data and compared to the laboratory analysis. The data were extracted using the Tekscan i-Scan software. Each measurement was captured in a frame with a sensor matrix expressing the pressure at the point. When the pressure sensors are placed in-between the tomatoes the sensors register a base pressure due to the static weight of the tomatoes on top of it. To accurately determine the transport induced pressures the base pressures were removed by subtracting these pressures from each data frame.

Field and laboratory data were compared and are presented in Figure 10 and Figure 11. Figure 10 shows the relationship between the two-layer laboratory analysis and the small box field analysis.

Figure 10 Correlation between field and laboratory pressure analysis for small boxes and the two-layer analyse (see online version for colours)

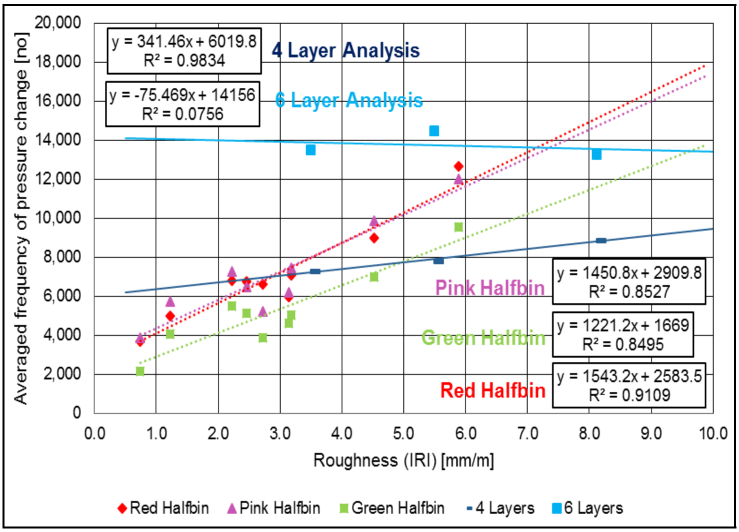


Although the data from the small box analysis does not exactly match the two-layer analysis the data fall within the same range. More data points should be collected to give a better accuracy for the two-layer analysis.

The four-layer and six-layer analysis along with the various halfbin analysis are presented in Figure 11. The four-layer laboratory analysis correlates closely with the halfbin field analysis except for the last data point as indicated by the arrow in Figure 11. The use of sand bags to represent the weight of tomatoes could jeopardise the accuracy of the pressure data because the sand bags behave as a single unit whereas stacked tomatoes move independently. Sand bags were used to limit the amount of tomatoes required for each experiment.

The six-layer analysis does not match any of the data trends and was not further considered. This could be as a result of the use of sand bags. Further testing is required to confirm this finding.

Figure 11 Correlation between field and laboratory pressure analysis for halfbins and the six-layer and four-layer analyse (see online version for colours)



3.2 Colour monitoring and consumer perspective

The HunterLab MiniScan was used for colour measurements. The minimum value for 'L' is zero corresponding to the colour black and the maximum value is 100 which is a perfect reflecting diffuser. The 'a' and 'b' values have no specific numerical limits. A positive 'a' corresponds to the colour red and a positive 'b' value corresponds to the colour yellow. Negative 'a' and 'b' values correspond to the colours green and blue respectively.

From each of the experimental setups four tomatoes were selected for colour monitoring. Each reading represents the average of three measurements as calculated by the miniscan. The measurements of bruised tomatoes were compared to the measurements of control tomatoes. For the green tomatoes two measurements were collected, one on the location of a bruise and one on a location where the tomato was not bruised.

No significant difference in the colour measurements were noted between the bruised locations and the control tomatoes. Colour measurements were therefore inconclusive. The rate of colour change was calculated. There are small differences in the rate of colour change between bruised and control tomatoes, but no clear trend was visible. Colour changes in bruised tomatoes are similar to the normal rate of colour change for non-bruised tomatoes.

There are limitations to only considering colour measurements. The colour measurements do not address the soft spots that appear on the tomatoes due to bruising.

Figure 12 is an example of tomatoes with soft spots where there was not a significant difference in colour between bruised and control tomatoes. The 'L', 'a' and 'b' values for the tomato indicated in Figure 12 versus the control tomato is presented in Figure 13 and Figure 14. Tomatoes with soft spots are less likely to be purchased by consumers and have lost economic value.

Figure 12 Identification of soft spots on tomatoes (see online version for colours)

Figure 13 'L', 'a' and 'b' values for bruised tomato (see online version for colours)

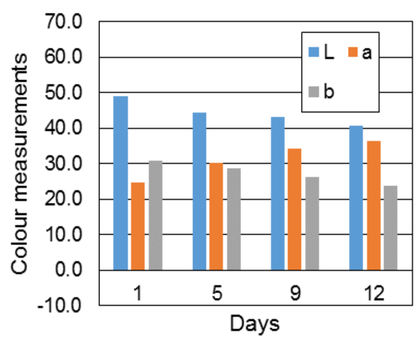
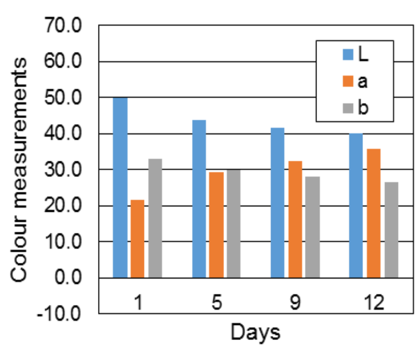


Figure 14 'L', 'a' and 'b' values for control tomato (see online version for colours)



Although it is difficult to quantify 'consumer perspective' because it varies from one observer to the next, the marketability matrix attempts to bridge the gap between damage and shelf life.

3.3 Experimental model

The purpose of the experiment was to determine if it is possible to estimate the loss in shelf life due to the roughness of the road. The experimental model was developed as follows:

- The energy generated due to different roughness values were compared to the energy generated at different amplitudes. A representative roughness value for the different amplitudes was calculated using the energy graph.
- The frequency of pressure change at the different roughness and amplitude values were compared to determine if the field and laboratory experiments obey similar rules.
- The marketability matrix and colour changes were related to damage and loss in shelf life.

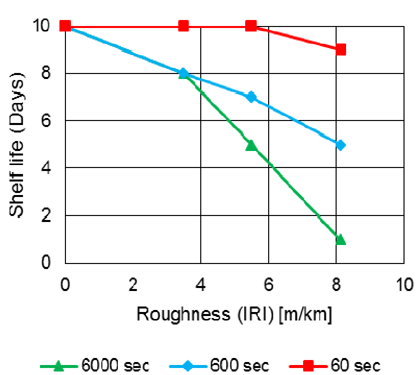
Figure 15 to Figure 17 shows the results of the marketability matrix analysis for the pink tomatoes. These are the tomatoes that are available in most supermarkets. The y-value in the equations represents the shelf life and the x-value represents the roughness. The tomatoes in the two-layer analysis have lost significant shelf life especially when tested at high amplitudes and over longer time periods. The tomatoes in the four and six-layer analysis have the highest remaining shelf life after the vibration test.

Figure 18 to Figure 20 shows the results of the marketability matrix analysis for the green tomatoes.

Green tomatoes are likely to be damaged when placed in the lower layers as compared to red tomatoes. Figure 21 and Figure 23 shows the results of the marketability matrix analysis for the green tomatoes.

If red tomatoes are placed in the lower layers, the lack of firmness allows the fruit to absorb more energy before damage becomes visible.

Figure 15 Shelf life predictions for pink tomatoes in the 1st and 2nd layers at the top (see online version for colours)



6,000 seconds:

y = –0.29 x + 10.0 for x ≤ 3.5

y = –1.73 x + 15.06 for x > 3.5

600 seconds:

y = –0.29 x +10.0 for x ≤ 3.5

y = –1.51 x + 14.28 for 3.5 > x ≥ 5.49

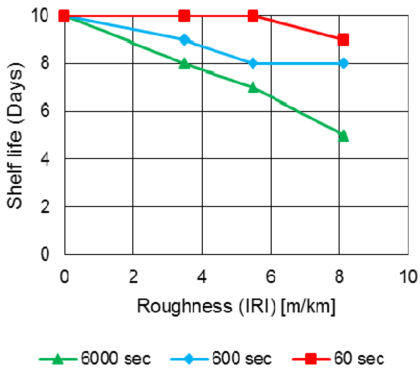
y = 6 for x > 5.49

60 seconds:

y = 10.0 for x ≤ 5.49

y = –0.38 x +12.09 for x > 549

Figure 16 Shelf life predicted for pink tomatoes in the 3rd and 4th layers (see online version for colours)



6,000 seconds:

$y = -0.73\ x + 9.86$

600 seconds:

$y = -0.57\ x + 10.0$ for $x \leq 3.5$

$y = 8$ for $3.5 > x \geq 5.49$

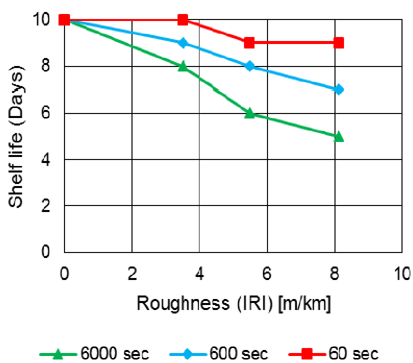
$y = -0.38\ x + 10.09$ for $x > 5.49$

60 seconds:

$y = 10.0$ for $x \leq 5.49$

$y = -0.38\ x + 12.09$ for $x > 5.49$

Figure 17 Shelf life prediction for pink tomatoes in the 5th and 6th layers (see online version for colours)



6,000 seconds:

$y = -0.73\ x + 10$ for $x \leq 5.49$

$y = -0.38\ x + 10.33$ for $x > 5.49$

600 seconds:

$y = -0.29\ x + 10.0$ for $x \leq 3.5$

$y = -1.01\ x + 12.52$ for $3.5 > x \geq 5.49$

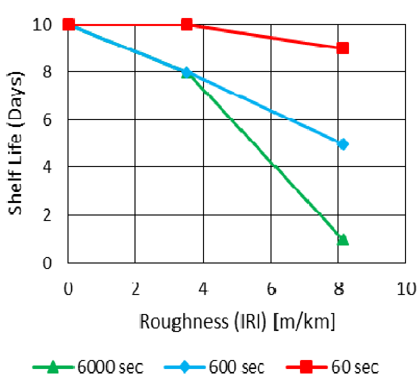
$y = 7$ for $x > 5.49$

60 seconds:

$y = 10.0$ for $x \leq 3.5$

$y = -0.43\ x + 11.52$ for $x > 3.5$

Figure 18 Shelf life prediction for green tomatoes in the 1st and 2nd layers (see online version for colours)



6,000 seconds:

$y = -0.57\ x + 10.0$ for $x \leq 3.5$

$y = -1.52\ x + 13.3$ for $x > 5.49$

600 seconds:

$y = -0.62\ x + 10.06$

60 seconds:

$y = 10.0$ for $x \leq 3.5$

$y = -0.22\ x + 11.73$ for $x > 3.5$

Figure 19 Shelf life prediction for green tomatoes in the 3rd and 4th layers (see online version for colours)

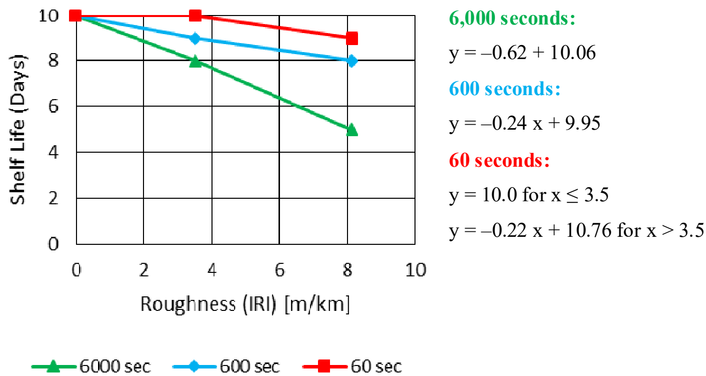


Figure 20 Shelf life prediction for green tomatoes in the 5th and 6th layers (see online version for colours)

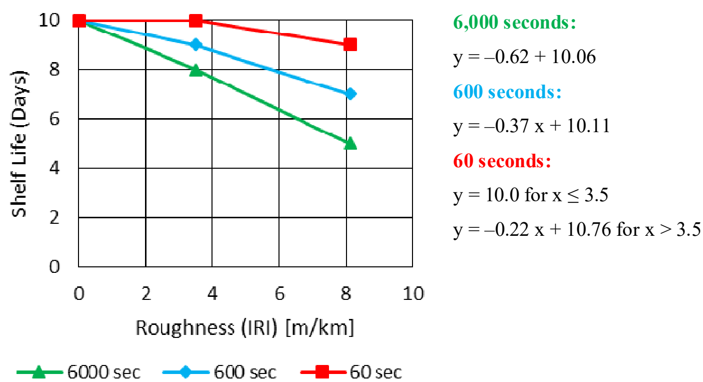


Figure 21 Shelf life prediction for red tomatoes in the 1st and 2nd layers (see online version for colours)

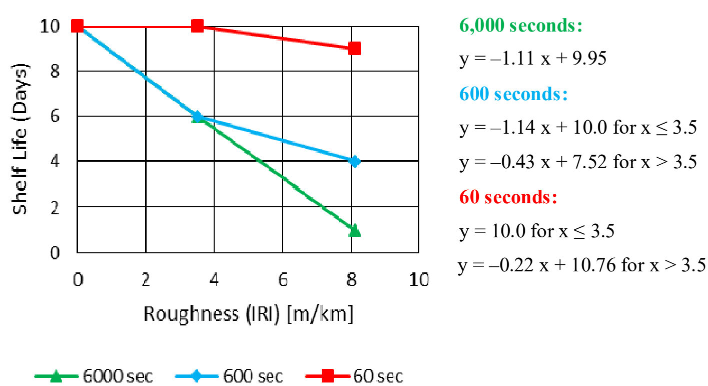


Figure 22 Shelf life prediction for red tomatoes in the 3rd and 4th layers (see online version for colours)

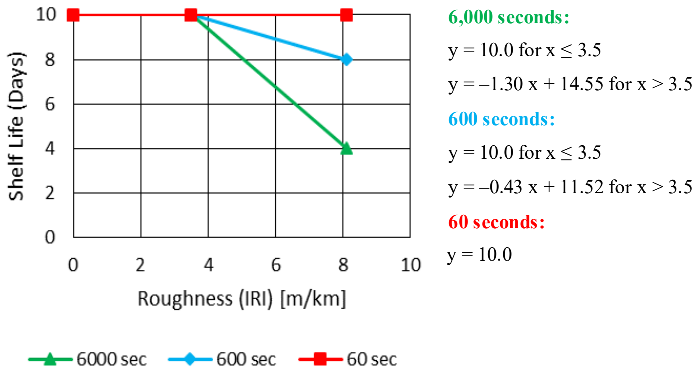
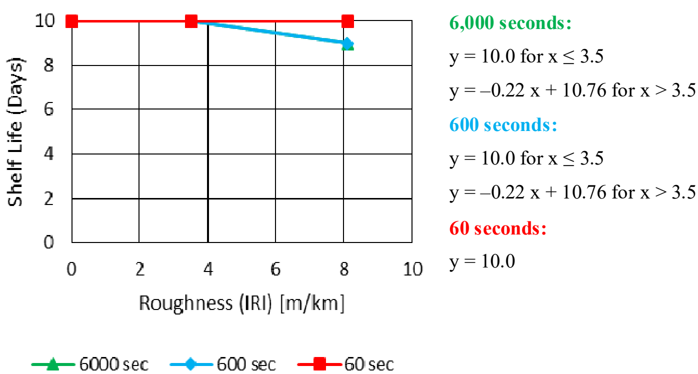


Figure 23 Shelf life prediction for red tomatoes in the 5th and 6th layers (see online version for colours)



The red tomatoes show more damage in the two-layer analysis compared to the green tomatoes. In the literature it was highlighted by Van Linden et al. (2006) and Van Zeebroeck et al. (2007) that physical damage increases with ripeness. Van Zeebroeck et al. (2007) reported that the bruising of tomatoes is affected by the contact time. Contact time is influenced by the ripeness of the fruit. During the two-layer analysis, the tomatoes had significant freedom of motion. The freedom of motion combined with the increase in contact time would result in more bruise damage for red tomatoes.

The pink tomatoes behaved in a similar manner to the green tomatoes. Caution should be used when interpreting these models. Further research and refinement of the models is required as these are specific to the type of tomatoes and trucks used.

3.4 Conclusions

The objective of this paper as formulated in the general introduction included the investigation of the relationship between road roughness and tomato damage. The effect that the ripeness of tomatoes has on the amount of damage and the role that two different packaging types played as method to contain produce during shipment was also considered.

3.4.1 Relationship between roughness and damage

Three different amplitudes correlating to roughness values of 3.5 m/km, 5.49 m/km and 8.12 m/km were used to evaluate the effect of road roughness during a laboratory analysis. This study indicated that as the roughness of the road increased so did the damage to the transported tomatoes, irrespective of the ripeness of the fruit and its position within the package. These finding are supported by several other studies by authors including Jarimopas et al. (2005) and Chonhenchob et al. (2009).

3.4.2 Relationship between ripeness and damage

Three different stages of tomato ripeness were investigated during the analysis. Tomato ripeness was based on the skin colour defined as red, pink and green. The effect of ripeness should be considered jointly with the position in the package which influence the contact time and pressure of loading during shipment. On well-maintained roads with roughness values less than 3.5 m/km red tomatoes in the top layers tend to damage more with an increase in transport time as compared to tomatoes in the lower layers. Green and pink tomatoes are more resistant to damage in the top layers than the red tomatoes.

3.4.3 Relationship between layer depth and damage

On all accounts, irrespective of the ripeness of the fruit, the highest loss in shelf life was visible in the upper layers. This is in line with the findings by Jarimopas et al. (2005) and O'Brien et al. (1965). For different combinations of frequencies and amplitudes, fruit can experience vibrations approaching 1.0 gravitational force. This can cause rotation, rubbing, skin discolouration and breakdown of surface tissue (O'Brien et al., 1965).

3.4.4 Practical implication of this study

This research attempts to create a model that relates tomato damage and loss in shelf life to the road condition, fruit ripeness and position in the container.

If two roads with different riding qualities serve as options to deliver produce to a market, the can be compared with the models presented in this paper. The cost implications relating to shelf life loss could be assessed and logistics planners could make informed decisions. Similar models can be developed to include other types of fruits and vegetables.

When vehicle operating and maintenance costs are also included in an analysis, it is possible to form a holistic view of the costs involved.

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