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Determining the Effects of Vibration Parameters and Packaging Method on Mechanical Damage in Golden Delicious Apples

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Abstract: This research was conducted to evaluate the effects of vibration frequency, vibration acceleration, packaging method, and vibration duration on the mechanical damage during apple transportation. The research was performed in 3 stages. Firstly, vibration frequency and vibration acceleration were measured on the truck-bed for determining the vibration frequency and acceleration distribution. Secondly, packaging transmissibility and vibration frequency sensitivity for all the packaging methods used in this research were measured. Thirdly, a laboratory vibrator, which simulates the road transportation under laboratory conditions, was used to obtain some factors influencing the mechanical damage during apple transportation. According to the results measured on the truck-bed, vibration frequency values were 8.19 Hz and 12.59 Hz for 5-10 Hz and 10-15 Hz frequency intervals, respectively. Furthermore, vibration acceleration values were 0.33 g and 0.63 g for 0.25-0.50 g and 0.50-0.75 g intervals, respectively. The highest packaging transmissibility was obtained for the volume packaging method, and packaging transmissibility was at similar high levels at the vibration frequency interval of 8-9 Hz for all packaging methods. Vibration frequency, vibration acceleration, packaging method, and vibration duration, which were taken into consideration as controlled variable parameters, significantly affected the equivalent severe bruise index at the 1% level of significance. Apples in the pattern packaging method had by far the lowest bruising, and the most suitable method for transit was pattern packaging.

Key Words: Apple, Transportation, Mechanical Damage, Vertical Vibration, Packaging Method

Golden Delicious Elma Çeşidinde Titreşim Parametreleri ve Paketleme Yönteminin Mekanik Zedelenme Üzerindeki Etkilerinin Belirlenmesi

Özet: Bu araştırma, elma taşımacılığı sırasında oluşan mekanik zedelenme üzerine titreşim frekansı, titreşim ivmesi, paketleme yöntemi ve titreşim süresi etkilerini araştırmak amacıyla yapılmıştır. Araştırma üç aşamada gerçekleştirilmiştir. İlk aşamada, yol koşullarında araç kasası üzerinde titreşim frekansı ve titreşim ivmesi ölçümleri yapılmış ve dağılım yüzdeleri belirlenmiştir. İkinci aşamada, araştırmada kullanılan üç farklı paketleme yöntemi için, paket iletkenlik oranları ve titreşim frekansı hassasiyet sınırları ölçülmüştür. Araştırmanın üçüncü aşamasında ise, elma taşımacılığı sırasında oluşan mekanik zedelenme üzerine etkili bazı faktörleri belirlemek için laboratuar koşullarında yol taşımacılığını simüle eden titreşim test düzeneği kullanılmıştır. Titreşim kuvvetlerinin etkisine bağlı olarak elma yüzeyinde oluşan zedelenmeler; zedelenme dağılımı (toplam zedelenme indeksi) şeklinde tanımlanmıştır. Yol koşullarına ilişkin araç kasası üzerinde yapılan ölçüm sonuçlarına göre, titreşim frekansı değerleri sırasıyla 8.19 Hz ve 12.59 Hz ortalama ile 5-10 Hz ve 10-15 Hz aralığında gerçekleşmiştir. Ayrıca titreşim ivmesi değerleri de, sırasıyla 0.33 g ve 0.63 g ortalama ile 0.25-0.50 g ve 0.50-0.75 g aralığında gerçekleştiği belirlenmiştir. Paket iletkenlik oranı en yüksek paketleme yönteminin hacimsel paketleme yöntemi olduğu belirlenmiş ve tüm paketleme yöntemleri için 8-9 Hz titreşim frekansı aralığında paket iletkenlik oranları yüksek çıkmıştır. Kontrollü değişken parametreleri olarak dikkate alınan titreşim frekansı, titreşim ivmesi, paketleme yöntemi ve titreşim süresi toplam zedelenme indeksi üzerinde %1 önem düzeyinde etkili olmuştur. Düzenli paketleme yönteminde elmaların daha düşük oranda zedelendiği ve yol taşımacılığına en uygun paketleme yönteminin düzenli paketleme yöntemi olduğu belirlenmiştir.

Anahtar Sözcükler: Elma, Taşımacılık, Mekanik Zedelenme, Düşey Titreşim, Paketleme Yöntemi

Introduction

Mechanical injuries are responsible for considerable decay of fresh fruits and vegetables. Produce discarded because of damage in the chain between the grower and the consumer is estimated at around 30-40% (Barchi et al., 2002). With regard to transportation, frequent attention has been devoted to delicate fruits such as apples. Singh and Xu (1993) reported that as many as

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80% of apples can be damaged during simulated transportation by truck, depending on the type of truck, package and position of the container along the column. Other results of tests carried out on apples during transportation confirm the high susceptibility of these fruits to mechanical vibrations and the great influence of the kind of container on damage (Schulte et al., 1990; Timm et al., 1996). Mechanical damage due to transport vibration was investigated on other species of fruits and vegetables such as peaches (O'Brien et al., 1969; Vergano et al., 1991; Aydın, 1993; Öğüt et al., 1999), oranges (Chesson and O'Brien, 1971), apricots (O'Brien and Guillou, 1969; Slaughter et al., 1993; Slaughter et al., 1998), tomatoes (Olorunda and Tung, 1985; Singh and Singh, 1992; Aydın, 1993; Hinsch et al., 1993; Özgüven and Vursavuş, 2002), grapes and strawberries (Fischer et al., 1990).

The vibrations due to transportation are influenced by road roughness, distance, travelling speed, load, and some characteristics of the truck such as the suspension and the number of axles (Berardinelli et al., 2003). The effects of the transportation on agricultural products depend on the type of packaging; some types of packaging, such as bulk bins, can remarkably amplify vibrations during transportation from the bottom to the top of the shipment column (O'Brien et al., 1965; O'Brien and Guillou, 1969; Chesson and O'Brien, 1971).

Damage inflicted on fruit is related to the energy available for bruising and the characteristics of the product. The energy available for bruising is in turn related to: (1) the suspension characteristics of the vehicle transporting the fruit, (2) the energy input to the system as a function of roughness of the road and vehicle speed, and (3) the properties and packaging of fruits.

Several different types of packaging such as the polystyrene soft cell tray, paper pulp tray, wood bin, bulk bin and corrugated fiberboard are used in order to transport apples. In recent years, some researchers have also focused on using polyethylene bags in apple and pear transportation (Schulte et al., 1990; Slaughter et al., 1998). Further, polystyrene soft cell master and foam cell master were also used to investigate apple damage during intrastate transportation (Schulte et al., 1990).

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. Hence, the effect of vertical vibration was investigated by neglecting the other vibration components in most studies performed in the past. O'Brien et al. (1969) reported that 6 directions of motion can be used to describe the vibration of the fruit. However, the primary cause of in-transit fruit damage was the vertical acceleration applied to the containers. The best method for investigating the effects of these operations is real road conditions but it is quite difficult to control the variables under these conditions. Therefore, random or sinusoidal vibration signals are used in order to conduct experiments related to the transportation of fruit and vegetables (ISO, 2001). The effect of sinusoidal vibrations on the quality of agricultural products has been studied by several researchers. Experiments were carried out in order to understand the reason for the in-transit injury of fresh fruits, determining their natural frequencies and to relate these to the vibration characteristics of the transportation (O'Brien et al., 1965; O'Brien and Guillou, 1969; Chesson and O'Brien, 1971). For this purpose, a laboratory vibrator powered by an electric motor with a table designed to oscillate on soft springs and a counterweight with attached to it was set up to provide amplitudes and frequencies covering the range usually measured on the truck. The mechanical behavior of oranges was analyzed using this apparatus (Cheson and O'Brien, 1971). Since the 1980s, a more modern system has been employed by Turczyn et al. (1986) to determine the cause of potato shatter bruising. These authors stressed 2 types of shipping containers of potatoes with sinusoidal vibrations according to the procedures outlined by the American Society of Testing and Materials (ASTM, 1979).

The objectives of the present study were (1) to measure and analyze the vibration frequency and vibration acceleration generated on the truck-bed under real road conditions for determining the vibration frequency and acceleration distributions, (2) to measure and compare the packaging transmissibility and vibration frequency sensitivity for all package methods used in this research, and (3) to simulate the transport vibration by means of a vibration simulator under laboratory conditions to investigate the effects of vibration parameters such as vibration frequency, vibration acceleration, and vibration duration, and packaging methods (paper pulp tray, pattern and volume packaging) on the mechanical damage during apple transportation.

Materials and Methods

The apples used in this study were of the Golden Delicious variety, which are 70-79 mm diameter. This variety was selected because it is quite susceptible to bruising, and bruises and abrasion are easy to see. The apples were carefully hand-picked in the 2001 season from an orchard in the village of Kamışlı near Pozantı in Adana province and placed in the corrugated fiberboard containers with paper pulp trays in the orchard. This procedure was followed in order to minimize any bruising that may occur from transporting the apples to the laboratory.

The vibration simulator used in this study was similar to that described by O'Brien and Guillou (1969) and Aydın (1993). A laboratory vibration simulator (Figure 1) powered by an electric motor (0.75 kW and 2790 min^{-1}) was used to provide amplitudes and frequencies covering the range measured on trucks, and also higher frequencies up to 27 Hz. Un damped forced vibrations were obtained by an actuating system that included adjustable weights on 2 counter-rotating shafts attached to the table and revolving in opposite directions, providing vertical vibrations only. The speed of the electric motor was adjusted by means of a speed control unit, which had 2.5 kW maximum powers. The magnitude and angular velocity of the rotating masses can be varied.

In this research, 3 packaging methods, namely paper pulp tray packaging, pattern packaging and volume packaging, were used. A paper pulp tray was placed into corrugated fiberboard and filled with apples (13 kg capacity). Apples were also filled by hand in the corrugated fiberboard triangularly for pattern packaging (9 kg capacity). For volume packaging, a wooden container was filled with apples randomly (12 kg capacity). The 3 types of commercial containers are illustrated in Figure 2.

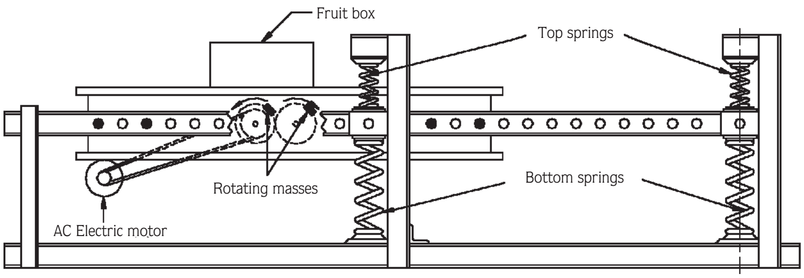

Figure 1. Laboratory vibration simulator.

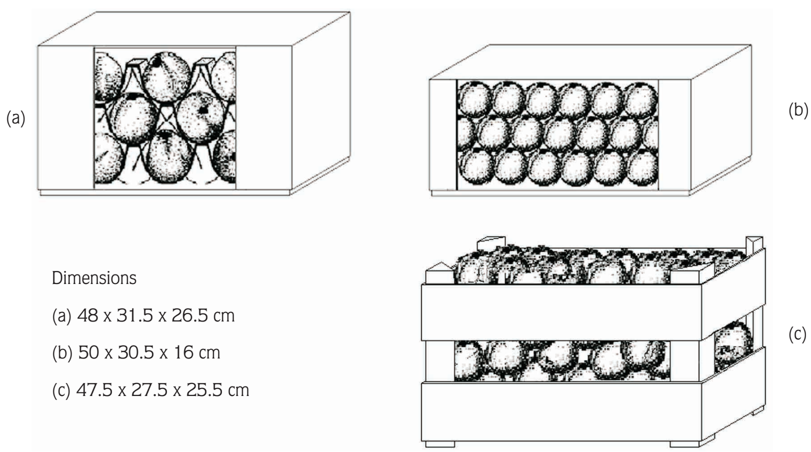

Figure 2. Containers used in paper pulp tray, pattern and volume packaging methods (drawings are only representations and are not to scale).

Each container was filled with 3 layers of apples. A macerated paper pad was placed on the wood bin bottom. Further, no padding was placed on the top of the fruit in the containers.

Vibration measurements were carried out on the truck-bed, which has two axles and suspension systems with a leaf spring in front and air-ride in rear for road conditions and on a vibration simulator for laboratory study. In the measurement of road conditions, an acceleration measurement device (Bruel & Kjaer, Vibration Meter Type 2511) and recorder (Level Recorder Type 2306) were used. The piezoelectric accelerometer (Bruel & Kjaer 4366) was mounted on the truck-bed floor in different positions 200 mm from the right wall of the truck. The accelerometer was connected to the acceleration measurement device and signals were plotted on graph paper by the recorder. Truck speed was held constant at 50 km h-1 in the measurements. This procedure was repeated for the front, middle and rear axle positions of the truck-bed. Vibration graphs plotted by the recorder in different positions were used in order to measure the acceleration and amplitude of the truck-bed. In these measurements, all of the data were taken into account to ignore the effects of truck-bed position because the loading position was not studied in this research. Vibration frequency values of the truck-bed were determined using a sine calculator program. Vibration graphs plotted by the recorder were also read and then vibration frequencies on the truck-bed were calculated by entering vibration acceleration and amplitude values into the program. In the tests, calculated vibration frequency and measured vibration acceleration values were used in order to obtain frequency and acceleration distribution percentages on the truck-bed. Therefore, distribution percentages of vibration frequency and vibration acceleration were obtained with intervals of 5 Hz and 0.25 g, respectively. Two of the average values, which give the highest distribution in the distribution percentages depending on intervals of vibration frequency and acceleration, were taken into account to be controlled variable parameters used in the laboratory tests. These averaging values selected as controlled variable parameters were 8.2 and 12.6 Hz for vibration frequency and 0.33 and 0.66 g for vibration acceleration.

Because the frequency of the vibration simulator table is directly related to the rotation number of the counter-weight, the frequency of the table was obtained with the revolution number of the electric motor. Therefore, the speed of the electric motor was adjusted by means of a speed control unit (Commander SE). The revolution number of the electric motor measured in rpm was divided by 60 s and the frequency of vibration simulator table was obtained in Hz. The acceleration of the vibration simulator table was directly measured using an acceleration measurement device and a piezoelectric accelerometer.

To measure packaging transmissibility, the container was placed on the vibration simulator table and subjected to vibration from 3 to 24 Hz at intervals of 3 Hz. The transmissibility of vertical vibration was measured at 2 stages. At the first stage, the accelerometer was mounted on the vibration table and vibration acceleration in the vertical direction was measured. At the second stage, the accelerometer was attached (using double-sided adhesive) to the lid of a container of apples and then vertical vibration acceleration was measured. This procedure was applied for all of the frequency values up to 24 Hz. Packaging transmissibility for 3 packaging methods was calculated using the following equation:

$$P_T = \frac{a_b}{a_t} 100 \qquad (1)$$

where P_T is the packaging transmissibility (%), a_b is the vibration acceleration on the container (g) and a_t is the vibration acceleration on the vibration table (g).

Apple damage, as defined by Peleg (1985), can be divided into 5 categories; None, Trace, Slight, Medium, and Severe. In this study, apple grades were determined based on only mechanical injury. After the vibration treatments, all apples were graded according to their bruise diameter. Digital callipers having a least count of 0.01mm were used to measure bruise diameter on the apple surface. Bruises smaller than 12 mm in diameter for equivalent diameter of aggregate bruises were not counted. Bruise categories were ranked by a damage scale as summarized in Table 1.

An equivalent severe bruise index (EBI) for defining the apple quality according to bruise categories was used:

% EBI = trace bruises (0.1) + slight bruises (0.2) + medium bruises (0.7) + severe bruises (1.0) (2)

Table 1. Damage scale used in evaluating protective qualities of apple packaging systems.

Rating index	Degree of damage	Equivalent diameter of aggregate bruises (mm)
0.0	None	<12
0.1	Trace	12-19
0.2	Slight	19-25
0.7	Medium	25-32
1.0	Severe	>32

The data recorded in the laboratory test conditions were statistically analyzed using the 4 factor randomized complete block design to study the effects of vibration frequency (8.2 and 12.6 Hz), vibration acceleration (0.33 and 0.63 g), packaging method (paper pulp tray, pattern packing and volume packing) and vibration duration (10, 15 and 20 min) on the EBI. Further, Duncan's multiple range test was used to compare the means. From the results of the analysis, the effects of the main factors and their interactions with the EBI were determined. Ten apples were taken from each box and 3 replications were conducted for each combination of variables, consuming a total of 1080 apples (average 250 kg). The research plan is given in Table 2.

Results and Discussion

Vibration Measurements on Truck-bed for Road Conditions

According to the results from the vibration measurement on the truck-bed, vibration frequency values were 35% at an interval of 5-10 Hz, and 28.75% at an interval of 10-15 Hz (Figure 3). Further, vibration acceleration values in the vertical direction on the truck-bed were 41.25% at an interval of 0.25-0.50 g and 26.25% at an interval of 0.50-0.75 g (Figure 4).

The average values at intervals of 5-10 Hz and 10-15 Hz were 8.19 Hz and 12.59 Hz, respectively. In the same manner, the average values at intervals of 0.25-0.50 g and 0.50-0.75 g were 0.33 g and 0.63 g, respectively. Maximum and mean vibration values obtained under road conditions on the truck-bed are given in Table 3.

The vibration frequency and acceleration values measured in this research are close to those measured by O'Brien et al. (1969), Aydın (1993), Hinsch et al. (1993), Slaughter et al. (1993) and Pang et al. (1995) on truck-beds with different axles and suspension systems. According to Peleg (1985), frequency values on the truck-bed range between 3 and 200 Hz and frequency

Table 2. Research plan to study the effect of controlled variable parameters under laboratory conditions.

Controlled variable parameters	
Vibration frequency (Hz)	F_1 = 8.2 and F_2 = 12.6
Vibration acceleration (g)	A_1 = 0.33 and A_2 = 0.63
Packaging method	PM_1 = paper pulp tray; PM_2 = pattern packaging and PM_3= volume packaging
Vibration duration (min)	D_1 = 10, D_2 = 15 and D_3 = 20
Dependent variable	
Equivalent severe bruise index (%)	EBI

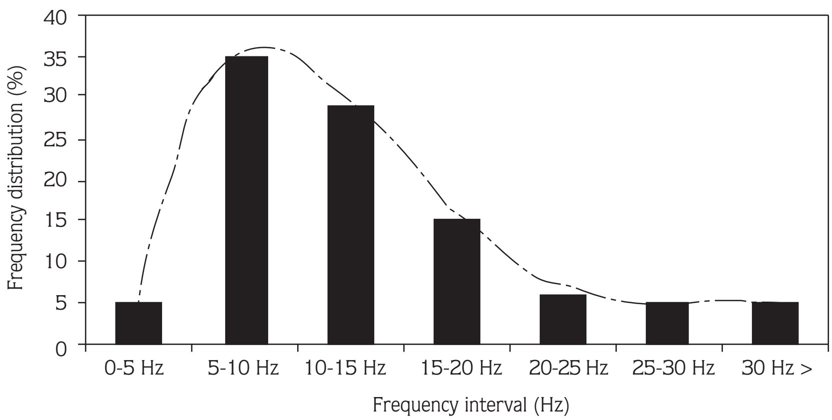

Figure 3. Distribution percentages of vibration frequencies on the truck-bed.

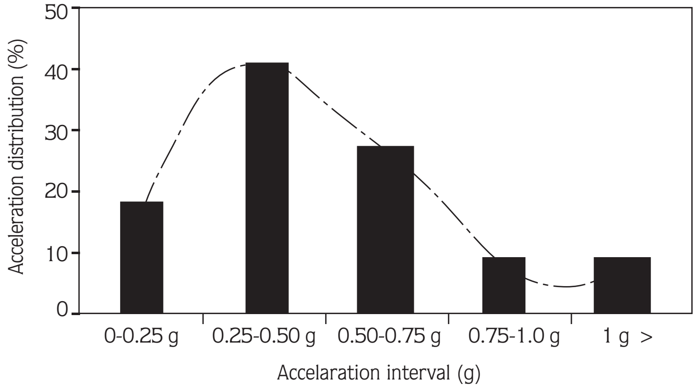

Figure 4. Distribution percentages of vibration accelerations on the truck-bed.

Table 3. Vibration parameters obtained under road conditions.

	Values	
Measured parameters	Mean	Maximum
G (amplitude, mm)	1.493	0.48
a (acceleration, g)	14.21	2.94
f (frequency, Hz)	1.20	34.85

levels above 50 Hz are insignificant. Our findings on the truck-bed in this research are in agreement with those reported by Peleg (1985).

Measuring the Packaging Transmissibility of Three Packaging Methods

The vibration transmissibility of 3 packaging methods to vertical vibration is shown in Figure 5. This figure shows at which frequencies the apples in the top of the containers vibrate at acceleration levels higher than the vibration table up to 15 Hz for paper pulp tray and pattern packaging and up to 18 Hz for volume packaging.

As seen in Figure 5, the transmissibility ratio for all packaging methods was measured at a maximum level of 9 Hz. At this frequency value, the transmissibility ratio for the PM1 and PM3 packaging methods reached approximately to transmissibility ratio of 160%. Distance from the horizontal axis of 100% determines the dimensions of vibration transmissibility. The values on the horizontal axis show that the top surface of the apple container vibrates at higher acceleration levels than the vibration simulator table. This seems to indicate that in selecting packaging frequencies between 3 and 15 Hz are the most critical for all packaging methods.

The Effect of Controlled Variable Parameters on the EBI

The analysis of variance results showed that vibration frequency (F), vibration acceleration (A), packaging method (PM) and vibration duration (D), which were used as controlled variable parameters in the laboratory tests, significantly affected the EBI (Table 4). The effects of the main factors were the most significant. Among the first-order interactions, the order of importance was FxA, AxPM and AxD, all being significant at the 1% level of significance. Among the second-order interactions, FxD, FxAxD and AxPMxD were significant at the 5% level of significance. Duncan's multiple range tests performed to determine the differences among the means of the main factors are given in Table 5.

The results showed that for the main factors pattern packaging (PM2) was the best method of interior packaging, followed by the paper pulp tray (PM1) and volume packaging (PM3). Volume packaging produced the highest damage levels. The vibration duration of 20 min caused damage levels higher than the other 2 durations for all packaging methods and EBI values, which means that high bruise dimensions in the apple containers were increased by an increase in vibration duration. Duncan's multiple range tests showed (Table 5) that the difference between PM1 and PM3 was not significant. Further, the differences among the vibration durations were significant at the 1% level. Mohsenin (1978) and Schulte et al. (1990) reported that an increase in the distance travelled raised the percentage of fruit bruised during transportation. The test results obtained in this study were similar to those obtained by Mohsenin (1978) and Schulte et al. (1990).

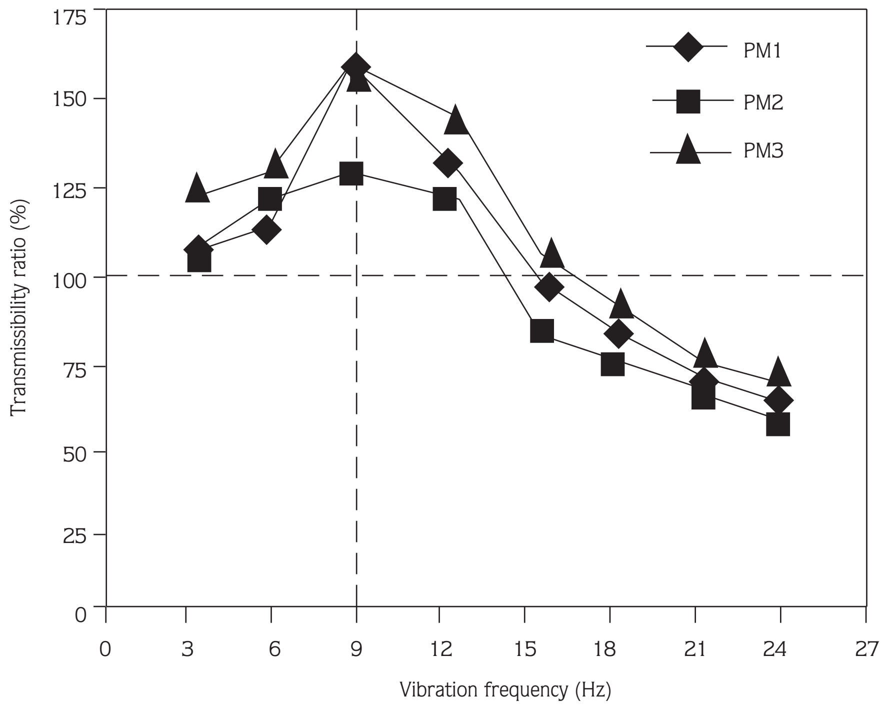

Figure 5. Transmissibility ratio of 3 packaging methods.

Table 4. F-values from ANOVA on the main effects and interactions.

Source of variation	DF	EBI
Vibration frequency (F)	1	54.9180**
Vibration acceleration (A)	1	132.4467**
FxA	1	50.6545**
Packaging method (PM)	2	17.1208**
FxPM	2	0.5053^{ns}
AxPM	2	26.3803**
FxAxPM	2	0.2724^{ns}
Vibration duration (D)	2	43.1185**
FxD	2	3.2547*
AxD	2	6.2323**
FxAxD	2	3.4209*
PMxD	4	2.2161^{ns}
FxPMxD	4	0.9007^{ns}
AxPMxD	4	3.2202*
FxAxPMxD	4	1.1052^{ns}
Error	72	

F: vibration frequency; A: vibration acceleration; PM: packaging method; D:vibration duration
DF = degrees of freedom, EBI = equivalent severe bruise index, ns = not significant
** Significant at the 0.01 level of significance, * Significant at the 0.05 level of significance

Table 5. The Duncan's multiple range tests of EBI values for the main factors.

Packaging method	EBI (%)
PM_1 (paper pulp tray)	22.51b
PM_2 (pattern packaging)	14.87a
PM_3 (volume packaging)	26.87b
Vibration duration (min)	
D_1 (10)	11.93a
D_2 (15)	21.11b
D_3 (20)	31.21c

The columns not followed by the same letter are significantly different at the 1% level of significant as judged by Duncan tests.

Figure 6 shows the effect of vibration frequency by vibration acceleration interaction on EBI values. Increasing vibration acceleration for each vibration frequency increased the EBI. This increase was due to the fact that packaging transmissibility measured at 9 Hz was close to 8.2 Hz vibration frequency. Further, it was observed in the test that when combinations of amplitudes and frequencies of vertical vibrations in the top layer of fruit are sufficient to produce accelerations approaching 1.0 g the top apples move freely because they receive sufficient energy from the vibration table to make them intermittently weightless. A comparison between 8.2 and 12.6 Hz vibration frequencies showed that the EBI was higher at 8.2 Hz than at 12.6 Hz vibration frequency.

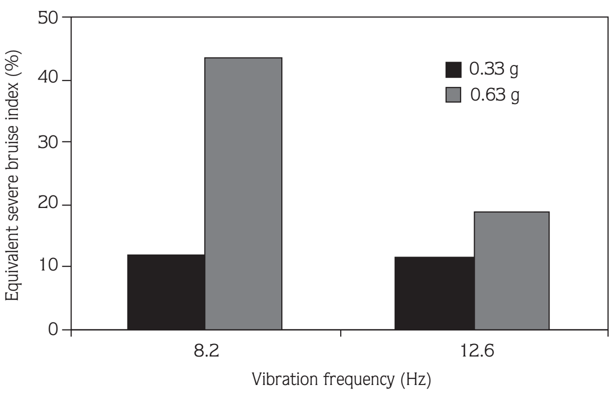

Figure 6. Effect of vibration frequency by vibration acceleration interaction on the EBI.

The effect of vibration acceleration by vibration duration interaction on the EBI is shown in Figure 7. EBI values in the vibration acceleration of 0.63 g increased from 18.30 to 44.87% with an increase in the vibration duration compared to 5.55 to 17.56% in the vibration acceleration of 0.33 g. The lowest and highest EBI values among the combinations were 5.55% and 44.87% for 0.33 g by 10 min and 0.63 g by 20 min interactions, respectively. Consequently, 0.33 g vibration acceleration was compared with 0.63 g and EBI values were as much as 3 times greater at 0.63 g as seen in Figure 7.

Figure 8 shows that as vibration duration is increased from 10 to 20 min the bruise dimensions of the apples in the container for both frequencies increase. A similar trend to vibration acceleration by vibration duration interaction was obtained in this interaction. The relationship among the combinations was determined

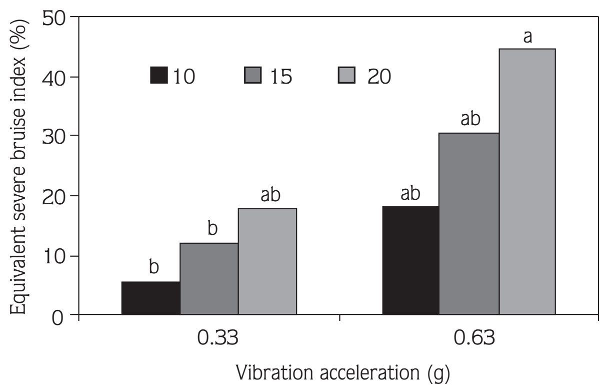

Figure 7. Effect of vibration acceleration by vibration duration interaction on the EBI.

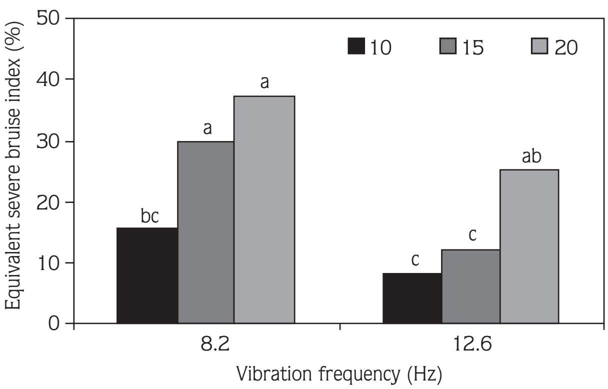

Figure 8. Effect of vibration frequency by vibration duration interaction on the EBI.

according to Duncan's multiple range tests and is shown in Figure 8. The highest and lowest EBI (%) values among the combinations were 37.36% and 8.22% for 8.2 Hz by 20 min interactions and 12.6 Hz by 10 min interactions, respectively. This sensitivity to 8.2 Hz can be explained by the results of the packaging transmissibility. As obtained in the packaging transmissibility ratio, transmissibility was the its maximum at 9 Hz vibration frequency. Therefore, when the vibration frequency of 8.2 Hz, which was close to the vibration frequency of 9 Hz obtained in packaging transmissibility, and vibration duration of 10, 15 and 20 min interact with each other the bruise dimensions of the apples in the containers increase.

Figure 9 shows the effect of vibration acceleration by packaging method interaction on the EBI. The lowest EBI value among the combinations was 4.97% for a vibration acceleration of 0.33 g by the PM1 packaging method interaction. This case changed for 0.63 g vibration acceleration and the highest EBI value was 40.05% for 0.63 g by the PM1 packaging method interaction. In particular, apples packed in the trays for paper pulp tray packaging offered higher damage due to possible bouncing of the apples inside their cells at high acceleration levels. Therefore, cushioning material can be put on top of the containers to reduce the movement of the apples. However, there will be an additional cost and inconvenience in handling if cushioning materials are used routinely. The relationship among the combinations was determined according to Duncan's multiple range tests and is shown in Figure 9.

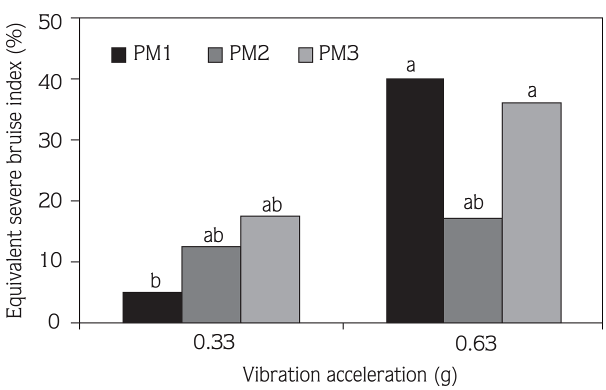

Figure 9. Effect of vibration acceleration by packaging method interaction on the EBI.

Another packaging method that cause high bruise dimensions and consequently, high EBI values among the combinations at high acceleration was volume packaging (Figure 9). Wooden container used for packaging has a rigid structure and high packaging transmissibility ratio. Therefore, most of the vibration forces transmitted from the vibration table to the apple container are absorbed by the apples in the containers and cause bruising of the apples. The reason for these bruises can be attributed to the fact that such forces in the top layer approached 1.0 g, causing some of the apples to be periodically weightless. Weightlessness allowed the apples to rotate and to bump against each other. This movement caused the surface discoloration and cell wall fatigue, and consequently bruising damage in apples.

Conclusions

This study showed that vertical acceleration frequency and magnitude developed by a truck-bed under road conditions were maximum at vibration frequencies of 5-10 and 10-15 Hz. The greatest acceleration distribution occurred at vibration accelerations of 0.25-0.50 and 0.50-0.75 g. Packaging transmissibility studies indicated that all the packaging methods were most sensitive to a vibration frequency of 9 Hz, which was a common vibration frequency measured on a truck-bed. In particular, the top layer of the wooden container was often subjected to acceleration amplification.

Laboratory studies indicated for controlled variable parameters that apples sensitive to a vibration frequency of 8.2 Hz and vibration acceleration of 0.63 g for all packaging methods would be subjected to more damage. However, apples packed by pattern packing methods produced the lowest damage levels and EBI values, followed by the paper pulp tray and volume packaging methods. The paper pulp tray packing method at high vertical acceleration (0.63 g) had the highest bruise potential because of apple size variations within counts. Therefore, trays used should be sized to provide a slight clearance in the carton and fruit of similar size should be used in paper pulp tray packaging to reduce bruise damage. Further, the use of top cushioning materials for all of the packaging methods can help in reducing bruising; however, the cost and inconvenience of using them seemed prohibitive.

The results obtained in the present work should be studied for different factors such as stack number, packaging position, suspension type and padding material use to guide future research on the effects of transportation on the quality of apples.

Acknowledgments

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