VIBRATION OF FRESH FRUITS AND VEGETABLES 
DURING REFRIGERATED TRUCK TRANSPORT

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ABSTRACT. Fresh fruits and vegetables experience losses enroute to market that are caused by mechanical injuries. Past studies have indicated that transit vibration contributes to this loss, and may be more important than impacts as a source of damage. In cross-country tests of cherries, nectarines, and pears in semi-trailers equipped with steel-spring suspension systems, highest Power Spectral Density (PSD) levels were found at about 3.5 Hz. In this study, PSD is used to mean acceleration spectral density. Other frequencies with high PSD levels were 9, 18, and 25 Hz. Similar results were found in tests with fresh tomatoes. However, in trailers equipped with an air-ride suspension and loaded with tomatoes, the PSD levels were attenuated at 3.5 Hz, and were reduced at other frequencies. The highest PSD levels were found at the rear of the trailer, with resonance in the loaded boxes occurring at some frequencies. Horizontal acceleration was much less than the vertical acceleration.

Understanding acceleration levels and frequencies that occur during shipment of perishables in refrigerated trailers will help to determine methods that will dampen the vibration energy and reduce the present losses in produce quality. Keywords. Air-ride, Leaf-spring, Resonance, Pears, Tomatoes, Cherries, Nectarines.

Fresh fruits and vegetables are subjected to injuries during handling, transportation, and distribution. Cherries, tomatoes, nectarines, and Bartlett pears have demonstrated these losses, ranging from 15 to 68% of their total market losses (Ceponis and Butterfield, 1974, 1981, 1985; Ceponis and Cappellini, 1985). “The basis for management of quality is the prediction of damage resulting from the susceptibility of the produce to the hazards of distribution” (Schoorl and Holt, 1982). O’Brien et al. (1963) also stated that, “Two factors affect the bruising of fruits: the magnitude of the force and number of times this force is repeated at a given location.” It has been suggested, however, that vibration may cause more bruising than impacts (Goff and Twede, 1979). Apple bruising was influenced by the quality of the road, shipment distance, and the type of container in which they were packed (Schulte-Pason et al., 1989). Reducing vibration and rubbing of peaches during transport from the orchard to the packinghouse reduced surface discoloration (Phillips, 1988). Laboratory tests have shown that table grapes positioned on the top layer of a stack sustained more damage than when they were in the bottom layer. The damage was a result of acceleration levels in the top layer being twice that of the lower ones (Fischer et al., 1989).

OBJECTIVES

The objectives of our study were to: 1) determine the acceleration frequencies and relative amplitudes occurring in loads of fresh fruits and vegetables during commercial cross-country tests in refrigerated trailers with commonly-used steel-spring suspension systems; and 2) compare the vibration levels of refrigerated steel-spring trailers with air-ride suspensions.

EXPERIMENTAL METHODS

FRUIT TESTS

A full, refrigerated trailer load each of California cherries, nectarines, or Bartlett pears was loaded at a commercial packinghouse in their respective production area in California and transported on interstate highways to east coast markets between Baltimore and New York City, a distance of about 4600 km (2,900 miles). All fruit were packed in corrugated fiberboard boxes and unitized on disposable softwood pallets. Plastic netting was used to secure the cherry boxes to the pallet, non-metallic strapping was used for the nectarine boxes, and palletizing glue (which has strength in shear but not in tension) was used for Bartlett pears. All fruit were cooled to, and shipped at about 1 C (34 F).

The palletized boxes were loaded by forklift into 14.6 m (48 ft) long x 2.6 m (8.5 ft) wide refrigerated highway trailers. One full trailer load each of cherries and nectarines, and two of Bartlett pears were shipped from California. All four trailers had steel-spring suspensions (Series 7600-7700-7800, Hutchens Industries, Inc., Springfield, MO 65802). The tractors also had steel-spring suspensions. Gross vehicle weights were not obtained.
TOMATO TESTS
Separately, four shipments of fresh market tomatoes were made from Nogales, Arizona, to Los Angeles, California, a distance of about 900 km (575 miles), most of which was on Interstate 10. All fruit were packed in part-telescope fiberboard boxes and unitized on softwood pallets. Palletizing glue and metal straps were used to secure the boxes to the pallets. The tomatoes were shipped at about 13°C (55°F).

These four tomato tests traveled the same highways from one shipper in Nogales, Arizona, to one receiver in Los Angeles, California. The same driver, and one tractor, which was equipped with an air-ride suspension on the drive axles, was used for all four tests. The gross weight of each load was about 35,900 kgs (79,000 lb). For two of the tests, a 14.6 m long x 2.6 m wide refrigerated trailer was equipped with a steel-spring suspension as described above. The other two tests used a similar trailer that was equipped with an air-ride suspension (Hendrickson Turner, Canton, OH 44707).

VIBRATION ANALYSIS
Piezoelectric accelerometers (Model 308M310, PCB Piezotronics, Depew, NY) were attached on the top, middle, and bottom boxes on one pallet in the center of the trailer, and to similarly located boxes on the rear pallet in the trailer. The top boxes were about 1.8 m (6 ft) above the floor. These six accelerometers were positioned to measure acceleration in the vertical direction, and were held in place with small “C” clamps. An additional accelerometer was attached to the top-center box on the rear pallet in the trailer, and was positioned to sense horizontal acceleration perpendicular to the direction of travel.

Two accelerometers were mounted to the floor of the trailer, one in the center and one at the rear, next to the previously described test pallets to measure vertical acceleration. They were held in place with double-sided adhesive foam tape (Scotch Cat. 114, 3M Company, St. Paul, MN 55103).

The accelerometers were connected by wire to a 9-channel shock recorder (Model MSR-1, Instrumented Sensor Technology, Lansing, MI 48910). One 5 s sample (625 readings) was taken every 15 min on the four east coast shipments, and one 10 s sample (1,250 readings) was taken every 3 min on the four Nogales/Los Angeles shipments. This data sampling rate (125 samples/s) provided frequency information up to 62.5 Hz. The recorder used a low-pass anti-aliasing filter at 340 Hz. To minimize aliasing, we looked only at data below 30 Hz. Caruso and Silver (1976) found that PSD levels for frequencies above 50 Hz were insignificant.

On arrival at the destination market, the instrumentation was retrieved, and the data were transferred to computer for analysis using EDR2S software (Instrumented Sensor Technology). The results are presented in terms of Power Spectral Density (PSD) plots, which at any given frequency show the variance of the root-mean square (rms) acceleration amplitude about a mean value of zero G (1 G equals the acceleration of gravity). The peak G values can be estimated using the method described by Brandenburg and Lee (1985).

The average rms (root mean square) acceleration level was determined over a 5 Hz frequency band for both the steel-spring and air-ride suspension trailers used in the tomato tests. The regions selected, 2.5 Hz, 17.5 Hz, and the entire frequency range of 0 to 62.5 Hz, show the differences in suspension types, but are not necessarily the critical frequency regions for a particular commodity.

RESULTS
FRUIT TESTS
Refrigerated trailers with steel-spring suspensions had the highest vertical PSD level on the floor at the rear position, regardless of the commodity, in the fruit tests (figs. 1a-c). Peaks occurred at about 3.5 Hz, with other less severe peaks at about 9, 16 to 18, and 25 Hz. The vibration at 3.5 Hz corresponds to the harmonics of the trailer suspension, while the higher frequencies correspond to the trailer structure’s natural frequencies (Ostrem and Godshall, 1979). The PSD curve for the center-floor position was essentially zero above 5 Hz, but not for the rear floor position.

The rear floor PSD results near 3.5 Hz for cherries, nectarines, and pears were about 0.05, 0.13, and 0.16, respectively. Therefore, 99.7% of the 3.5 Hz peak

Figure 1a–In-transit vertical vibration at two locations on the floor of a refrigerated trailer equipped with a steel-spring suspension and loaded with cherries, California to Baltimore, 1991.

Figure 1b–In-transit vertical vibration at two locations on the floor of a refrigerated trailer equipped with a steel-spring suspension and loaded with nectarines, California to Philadelphia, 1991.
accererations observed at this location should be within ±0.96, ±1.53, and ±1.68 G, respectively (Brandenburg and Lee, 1985).

For some frequencies between 5 and 30 Hz, the top box often vibrated considerably more than the middle and bottom boxes. For example, from about 8 to 10 Hz, the top box of pears loaded on the rear pallet exhibited about three times the PSD level of the bottom box, figure 2. The PSD values at 8.6 Hz were about 0.0030, 0.0016, and 0.0008 for the top, middle, and bottom box, respectively. Therefore, 99.7% of the peak accelerations observed should be within ±0.24, ±0.18, and ±0.12 G, respectively. The stack of boxes resonated near this frequency, so acceleration and displacement were amplified from the bottom to the top of the stack. If the pears also resonated within the box at this frequency, considerable bruise damage could result. These boxes had resonant characteristics at several frequencies, which may depend upon the type of fruit, package and packing method, and palletizing method.

**TOMATO TESTS**

The vertical PSD levels at the rear of steel-spring trailers used in the tomato tests were similar to those found in the fruit tests, figure 3. The PSD levels for the trailer with the air-ride suspension were lower, and did not have the high value at 3.5 Hz. The air-ride suspension had prominent acceleration peaks near 2, 6, and 9 Hz, but these were relatively low.

The average vertical acceleration levels in the middle of steel-spring trailers were 36% of those at the rear position. In air-ride trailers, these accelerations were 59% of those at the rear.

At the rear of the trailer, the average rms g acceleration for the air-ride suspension was 53% of that observed in the steel-spring suspension in the 0 to 5 Hz range, while it was 63% for the range of 0 to 62.5 Hz, table 1. In the center of the trailer, the average rms g acceleration for the air-ride suspension was less than 60% of that observed for the steel-spring suspension in the low frequency range, while it was comparable to that observed for the steel-spring suspension at frequencies above 15 Hz.

The horizontal acceleration recorded on the top box of the rear pallet was about 50% of the vertical acceleration in trailers with the steel-springs, while it was 38% in air-ride trailers, figs. 4a, b. The horizontal PSD levels for these two trailers with two suspension types were nearly the same, but vertical PSD levels were very different.

Table 1. Mean vertical acceleration levels (rms g) on the floor of refrigerated trailers*

<table>
<thead>
<tr>
<th>Location in trailer and suspension type</th>
<th>Frequency range</th>
<th>RMS G</th>
<th>RMS G</th>
<th>RMS G</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0-5 Hz</td>
<td>15-20 Hz</td>
<td>0-62.5 Hz</td>
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</tr>
<tr>
<td>Rear:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel spring</td>
<td>0.125</td>
<td>0.088</td>
<td>0.355</td>
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<tr>
<td>Air ride</td>
<td>0.066</td>
<td>0.050</td>
<td>0.225</td>
<td></td>
</tr>
<tr>
<td>Air/Steel (%)</td>
<td>53</td>
<td>57</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Center:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel spring</td>
<td>0.063</td>
<td>0.033</td>
<td>0.120</td>
<td></td>
</tr>
<tr>
<td>Air ride</td>
<td>0.037</td>
<td>0.033</td>
<td>0.130</td>
<td></td>
</tr>
<tr>
<td>Air/Steel (%)</td>
<td>59</td>
<td>100</td>
<td>108</td>
<td></td>
</tr>
</tbody>
</table>

* By location and suspension type, and the ratio of air to steel at each location, 4 tomato tests, 1992.
DISCUSSION
Interstate highway shipments of refrigerated trailers equipped with steel-spring suspensions and loaded with fresh cherries, nectarines, and Bartlett pears show the highest vertical acceleration levels at about 3.5 Hz. There were characteristic lower acceleration levels at about 9, 18, and 25 Hz. Similar results were obtained with full loads of fresh tomatoes in similar equipment. However, when tomatoes were loaded in refrigerated trailers with air-ride suspensions, the high vertical acceleration levels at 3.5 Hz did not occur at the rear of the trailer, but low to moderate accelerations at 6, 9, and 15 to 18 Hz did.

CONCLUSION
This study shows that:
- Vertical acceleration frequency and magnitude developed by a steel-spring suspension refrigerated trailer traveling interstate highways was similar for loads of packaged and palletized cherries, nectarines, pears, and tomatoes. The greatest acceleration occurred near 3.5 Hz. The top boxes in a stack were often subjected to acceleration amplification.
- Vertical acceleration magnitudes developed by an air-ride suspension trailer traveling similar highways were much less than those for the steel-spring suspension. The high acceleration near 3.5 Hz was not present, but low to moderate accelerations at 6, 9, and 15 to 18 Hz did exist.
- The center of both the steel-spring and air-ride trailers developed much less severe accelerations than did the rear.
- Horizontal accelerations perpendicular to the direction of travel were much less than vertical accelerations for both suspension types.
- Commodities sensitive to vibration frequencies below 5 Hz will be subjected to less damage when transported in trailers equipped with air-ride suspensions.

Controlled tests should be conducted with packaged fruits and vegetables to determine the vibration frequencies and magnitudes that will result in damage to produce. The combined results may show the less damaging suspension type for produce transport, how to improve either suspension type, or what packaging systems should be designed.

REFERENCES