# Vibration and shock analysis of specific events during truck and train transport of food products

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**ABSTRACT (150 words)**

In international test standards and literature averaged vibration spectra of truck and train transports are reported. However, cargo is exposed to extreme levels of vibrations and shocks for which the averaged vibration data are not representative. The objective of this study is to report evidence of the extreme vibrations and shocks during truck and train transport, and help food scientists design relevant vibration and shock simulation experiments. Results indicate that trains and trucks experience transient phenomena when traveling over train switches, accelerating and stopping the train, respectively road unevenness (e.g. potholes). The damping ratio (β) of shocks measured on the railcar is on average 0.05 ± 0.02, while on the truck 0.08 ± 0.02. Furthermore, the measured spectra of this study diverge from the spectra of international standards. A time-domain analysis indicates that traveling over cobblestones, and concrete pavement generates the most severe vibrations and shocks (dependency on truck velocity).



**Keywords**

Vibration measurements, transport simulations, event analysis



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## 1. Introduction

Fresh fruit and vegetables, as well as electronic goods, are susceptible to quality losses or failure due to vibrations and shocks. Vibrations and shocks during transport are categorized as an important contributor to the decrease in product quality (Gołacki, Rowiński, & Stropek, 2009; Van Zeebroeck et al., 2007). Since postharvest losses can be quantified between 30-50% of all food that is grown (Parfitt, Barthel, & Macnaughton, 2010), increased attention goes to this topic. Postharvest waste is defined as losses arising during transport, handling, and storage of food products before they reach the customer (Parfitt et al., 2010). International test standards (ISO -International Organization for Standardization- and ASTM -American Society for Testing and Materials-) guide researchers and (food) scientists to experimentally test products on transport vibrations. However, there is a mismatch between the vibrations measured in reality and the proposed test methods of the international standards. This study was performed to demonstrate the importance of transient phenomena when doing simulation tests and to further discuss the proposed test methods of international standards and the vibration spectra described in literature.

The international test standards (ASTM D4728 and ISO 13355) suggest the use of averaged vibration data in combination with applying time-compression (i.e. vibrations are artificially amplified to better replicate product damage) to simulate transport. As a consequence, the power spectral density levels (PSD-levels) differ from the ones that are measured in reality (Böröcz & Singh, 2016). An extensive field of literature has been devoted to reporting realistic vibration levels measured on different transport vehicles traveling on a regional transport network (without time-compression). Similar to the international standards, the latter mentioned papers also report averaged vibration data, i.e. root mean square-levels (RMS-levels) and PSD-levels, to characterize vibration measurements (Böröcz & Singh, 2016; Chonhenchob et al., 2009; Lu, Ishikawa, Kitazawa, & Satake, 2010; Rissi, Singh, Burgess, & Singh, 2008). However, limited evidence was reported in literature on the occurrence of transient phenomena during transport. Furthermore, the averaged vibration patterns to which test items are exposed during (recommended) transport simulations may differ substantially from the extreme levels of vibrations or shocks that are present during transport. Even the use of time compression in combination with averaged vibration data may not replicate damage that is produced by transients (Böröcz & Singh, 2016). Nevertheless, the influence of shocks on food products (for instance apples (Gołacki et al., 2009; Van Zeebroeck et al., 2007)) has been investigated in some papers. Therefore, in this study a thorough time-domain analysis of vibrations and shocks that occur during truck and railway transport was performed. Moreover, by offering additional insights on vibrations and shocks of specific events that occur during transport, researchers can simulate transports more realistically. With the information presented in this paper, researchers will be able to optimize experimental designs with better replication of damage to test items due to transport vibrations and shocks.

The literature on vibrations during transport is abundant; two categories of papers can be distinguished. The first category of papers (1) aims to identify the input spectra of different types of transport vehicles traveling on a regional transport network (Chonhenchob et al., 2009; Lu, Ishikawa, Shiina, & Satake, 2008; Rissi et al., 2008; Rouillard & Richmond, 2007). The papers often aim to identify several relevant parameters that influence the magnitude of the vibrations and shocks (Garcia-Romeu-Martinez, M-A Singh & Cloquell-Ballester, 2008; Lu et al., 2010; Singh, Singh, & Joneson, 2006). In the second category (2), a myriad of papers aims

to focus on the impact of vibrations and shocks on a specific food product. The influence of vibrations and shocks on an individual product (Van Zeebroeck et al., 2006), often fruit, or the interaction of products (Pang, Studman, & Ward, 1992) is regularly assessed. Also, the packaging strategy (i.e. damping and cushioning properties (Eissa, Gamaa, Gomaa, & Azam, 2012; Paternoster et al., 2017; Vursavus & Özguven, 2004)) and the configuration in a container (O'Brien, Gentry, & Gibson, 1965) was researched. Since vibrations and shocks have a direct influence on the product integrity and quality, it is essential to gain knowledge on the type and magnitude of the vibrations and shocks that occur during transport. Packaging engineers can adopt these insights to design a better packaging. On the one hand, a lack of knowledge could lead to insufficient packaging or cushioning of the products or, in other words, under-packaging of the products. An excess of protective cushioning, on the other hand, could lead to over-packaging. In the former scenario, under-packaging can easily be identified since the products will exhibit defects. The occurrence of over-packaging, which implies hidden costs, is more difficult to determine. From recent estimates, the total cost of over-packaging in Europe is 130 billion euros per year (Rouillard & Richmond, 2007).

The objective of the current paper is to identify vibration and shock patterns that are present when traveling over the Belgian road and railway network. Moreover, roads were segmented based on road type and speed limit to identify the vibration and shock characteristics. Similar research was performed by Jarimopas, Singh, & Saengnil (2005) indicating the influence of road type (laterite, asphalt, and concrete) with segmentation of the driving speed (20, 40 and 80 km/h) on vibrations and relating the measurements to damage of packaged tangerines. Current research further develops previous insights by also focusing on shock patterns when driving over different road types. While Lu et al. (2008) analyses shocks as individual events (e.g. metal joints, railway crossings), the current study investigates the magnitude and frequency of the shocks attributed to road type in combination with speed of driving. Furthermore, a time-domain analysis was completed to identify vibration and shock patterns that occur during railway transport (e.g. acceleration and stopping of a train, a passing train, etc.). The literature on shocks during railway transport is limited, which to the respect of the authors is remarkable due to the high magnitude of the shocks and the high frequency of occurring. This also emphasizes the unique contribution of this paper. In addition, shock analysis was performed in which the damping factor (β) and the acceleration amplitude (in time-domain) was calculated of diverse shocks measured during truck and railway transport. The last objective of this study was to identify the influence of cargo weight on the magnitude of the vibrations and shocks during transport. More extensive research on the influence of cargo weight on vibration levels was performed by Garcia-Romeu-Martinez et al. (2008), and therefore was used to benchmark research findings.

The scope of the paper is based on the Belgian transport network with specific reference to vibrations and shocks measured on trucks, with air-spring and leaf-spring suspension, and trains with leaf spring suspension within a Belgian context. The findings of this paper can be used by researchers and food scientists to simulate transport and optimize packaging design. The aim of this paper is to confront the simulation tester with the extreme levels of vibrations and shocks that are measured during transport and which are not reflected by the averaged power spectra described in international testing standards and literature.

## 2. Material & Methods

### *2.1 Experimental design*

Vibrations and shocks, defined as periodic or random in nature, respectively a single-event or transient phenomenon, were measured during truck and railway transport. The devices used to measure the vibrations included the following:

1) 3-Axial Accelerometers (SparkFun Triple Axis Accelerometer Breakout - ADXL337 – SEN 12786, SparkFun Electronics, Niwot, Colorado, USA)
2) Data acquisition board (National Instruments USB-6361 - Part Number: 782256-01, National Instruments, Austin, Texas, USA)
3) Laptop (Dell 1708FP, Dell, Round Rock, Texas, USA with MATLAB Release 2015a, The MathWorks, Inc., Natick, Massachusetts, United States.)
4) External battery (Solar-accu 12 V 60 Ah GNB Sonnenschein - NGSB120060HS0CA, Conrad, Oldenzaal, Netherlands)
5) Transformer (Voltcraft SWD-300/12 Omvormer 300 W 12 V/DC 12 V/DC - 513124 - 8J, Conrad, Oldenzaal, Netherlands)
6) Camera (GoPro Hero 4, GoPro, Paris, France)

The first five elements of the experimental set-up, listed above, are connected to each other. The accelerometers (1) had a sampling rate of 1e5 samples per second in order to also analyze high-frequency vibrations [bandwidth: 1600 Hz (X- and Y-axis / noise density: 175 μg/√Hz rms) and 550 Hz (Z-axis / noise density: 300 μg/√Hz rms)][I] and were linked by cable with the data acquisition board (2). The latter device transforms the electrical current passed along by the transducers to a digital signal that can be read by the programmable software of the computer (3). The software used in this research is Matlab 2015a. The devices were electrically charged by an external battery (4) connected with a transformer (5). The transformer converts the 12V DC into a 220V AC current. While performing measurements, a GoPro-camera (6), mounted over the shoulder of the driver, filmed the events during transport. As a consequence, the filmed events were matched with the corresponding vibration data.

Measurements were performed during seven transports ranging over two different modes of transport, more specifically train and truck transport. The accelerometers used in this study were attached on top of a wooden pallet (between food boxes and the pallet), in the case of the truck transports, and to a metal grill welded to the bogie of the railcar, in the case of the train transport. Since it is the industry standard to transport food products stacked on wooden pallets, for the purpose of this study accelerometers were mounted on top of a wooden pallet rather than on the container floor, as is the standard when doing vibration measurements. Furthermore, the railway vibrations were measured on the structure floor, i.e. fixed to a metal grill welded to the bogie of the railcar. Due to regulations out of our control, stakeholders and industry partners of this project were not able to unseal a container. Therefore, it was not possible to measure vibrations inside a container: this may cause limitations when comparing with research findings from the literature. However, this also results into unique insights on the vibration and shock patterns measured during transport. Vibration measurements were executed during the normal

[I] In the current study, no filter was applied to the signal. However, in order to prevent aliasing phenomena and to investigate the measured high-frequency vibrations, the sampling rate was fixed substantially high. The researchers are aware that the current results are predominantly informative within the bandwidth of the sensors.

operations or activities of the transport vehicle. As a consequence, all transport vehicles were loaded close to full capacity in the beginning of the transport and (completely or nearly) empty at the end of the transport. Therefore, it was possible to compare the difference in vibration patterns between transport vehicles with full or no cargo load. The transports, attended in the context of this research, are presented:

Truck transport [Specifications in Appendix]:

- Transport 1: 3/02/2016 (rec. time: 9hrs. 44mins) [air-ride spring]
- Transport 2: 12/04/2016 (rec. time: 3hrs. 26mins) [Leaf spring]
- Transport 3: 23/08/2016 (rec. time: 2hrs. 28mins) [air-ride spring]
- Transport 4: 27/09/2016 (rec. time: 1hrs 50mins) [air-ride spring]

Train transport

- Transport 1: 27/06/2016 (rec. time: 1hrs. 43mins) [Leaf spring with diesel engine]
- Transport 2: 2/08/2016 (rec. time: 2hrs. 10mins) [Leaf spring with diesel engine]
- Transport 3: 3/08/2016 (rec. time: 3hrs. 55mins) [Leaf spring with diesel engine]

### *2.2 Data analysis*

Complex shock motions, typically a half-sine function, are present during transport (Harris & Piersol, 2002). However, field data revealed that, due to the dynamics of the structure, the shock responses measured during truck and railway transport are best represented by a decaying sinusoid. Shocks occurring during truck transport (due to potholes, metal joints, etc.) or train transport (due to railway switches, etc.) might be represented by impulses that are damped over time due to the vehicle structure (e.g. tires, suspension, etc.). In order to facilitate shock simulation testing, transport shocks were analyzed by calculation of the damping ratio (β). The damping ratio is a function of the logarithmic decrement (λ), the frequency of the damped oscillation ($\omega_d$) and the damped period ($T_d$), which is the time between the two highest consecutive peaks. The logarithmic decrement is defined as the natural logarithm of the division of the acceleration amplitude of the highest peak ($x(T_1)$) divided by the acceleration amplitude of the second highest peak ($x(T_1 + T_d)$). Also the natural frequency of the damped oscillation ($\omega_n$) can be calculated (Thomson, 1993).

$$\beta = -\frac{\lambda}{\sqrt{\lambda^2 + T_d^2\omega_d^2}} = -\frac{\lambda}{\sqrt{\lambda^2 + (2\pi)^2}}$$

with

$$\begin{cases} \lambda = \frac{1}{\mathrm{d}}\ln\left(\frac{x(T_1)}{x(T_1+T_d)}\right) & with\ 'd' = integer\ number\ of\ successive\ peaks \\ \omega_d = \dfrac{2\pi}{T_d} & in\ \dfrac{rad}{s} \\ T_d = (T_2 - T_1) & in\ \ sec. \\ \omega_n = \dfrac{\omega_d}{\sqrt{(1-\beta^2)}} & in\ \dfrac{rad}{s} \end{cases}$$

Furthermore, a shock analysis was performed to evaluate the number of the measured accelerations (time-domain) above 5 m/s$^2$ that occur during transport. Moreover, the measured time-domain vibration signals were divided into intervals of 20 seconds. Afterwards, a histogram of all time-domain vibration data that were measured above 5 m/s$^2$ was calculated. The presented histograms in Section 3 indicate the average number of peaks during transport and one standard deviation up (respectively down). When dividing the average number of peaks by the sampling rate, the histogram is independent of the sample rate and can be compared with other vibration measurements (with different sample rate). Since a histogram of the measured accelerations (time-domain) above 5 m/s$^2$ was built for the different pavement types, different road conditions were benchmarked and compared.

Matlab R2015a was used to analyze the vibration signals and to build cumulative distribution functions (CDF) of the RMS and kurtosis values for different time-domain vibration segments. Moreover, the vibration data were partitioned in 1-second intervals, RMS and kurtosis was calculated and, afterwards, the cumulative distribution function was identified. Kurtosis is a statistical concept in which the shape of the measured signal is compared to the standard normal distribution. A positive kurtosis indicates a heavy-tailed distribution and a negative kurtosis a light-tailed distribution. Furthermore, average PSD plots were also calculated by performing multiple fast Fourier transforms and taking the linear average (bandwidth/frequency resolution 0.2 Hz). The technique can be presented by the formula:

$$Average(PSD)_f = \frac{1}{n}\sum_{i=1}^{n} PSD_{f,i}$$

with

$f = given\ frequency\ of\ the\ selected\ event$

$n = the\ amount\ of\ selected\ events$

## 3. Results & Discussion

In this research, the aim is to identify vibration and shock patterns during train and truck transport. Therefore, the effects that come into play with respect to vibrations and shocks of the different transport vehicles are sequentially analyzed and illustrated.

### *3.1 Vibration analysis – train and truck transport*

In Figures 1a and 1c, the cumulative distribution functions (CDF) of the RMS-values of the time-domain vibrations measured in the lateral (left-right), longitudinal (front-back) and vertical (up-down) direction of the train and truck transports are presented. The figures indicate that during both train and truck transports vertical vibrations are significantly higher of amplitude than vibrations in any other direction. The latter result was found by multiple researchers (Garcia-Romeu-Martinez et al., 2008; Rissi et al., 2008). Furthermore, during train transport, longitudinal vibrations are more pronounced than lateral vibrations, which is attributed to the forces that are build up and transferred along the concatenation of railcars. Since the cargo weight is of high influence on the magnitude of the vibrations (Garcia-Romeu-Martinez et al., 2008), the distinction was also made between vibrations measured in a transport vehicle with full and empty cargo. In the literature, unloaded vehicles are assumed to have on average higher vibration levels than loaded vehicles. In this study, results indicate that the railcar with full cargo had more severe vibrations than without cargo. The latter effect can be attributed to the stiffness of the spring of the leaf spring (suspension) that was not adapted to the cargo weight. In comparison, in truck transport with leaf spring suspension, the driver is ought to adapt the spring stiffness manually to the cargo weight to diminish the number of vibrations the cargo is subjected to. The effect of cargo weight on the vibration levels of truck transport with air-ride suspension is small or cannot be determined (Figure 1c). In Figures 1b and 1d, the CDF-plots of the kurtosis-values of the time-domain vibration signals for the two modes of transport are presented. During railway and truck transport kurtosis is positive, which suggest a heavy-tailed distribution. It is noteworthy that during truck transport lateral and longitudinal time-domain vibrations have higher kurtosis values than vertical vibrations. The latter effect is more pronounced with empty cargo.

The averaged spectral density plots of the truck with air-ride suspension and railcar with leaf-spring suspension, as would be presented in most of the articles in literature and in international standards, are depicted in Figures 2a-d. With respect to the truck transport, vibrations between 0.1 and 10 Hz are more significant than vibrations higher than 10 Hz. The lowest frequencies are commonly attributed to the road roughness, suspension, and tires (Singh et al., 2006). The PSD plots of the vibrations measured during train transport indicate that also high-frequency vibrations (>150 Hz) of high magnitude are present. The latter effect can be attributed to the mounting of the accelerometer on the bogie or the structure floor of the railcar. Furthermore, the dynamics interaction of the couplers between the railcars impedes the analysis of the measured vibrations and shocks. Inside a railcar container, vibrations higher than 150 Hz may be damped and significantly reduced in amplitude. However, current research can add insights to the origin and magnitude of the vibrations measured in railcars (leaf-spring suspension). Since literature on the vibrations and shocks that occur during railway transport is underdeveloped, every element of information that can add to knowledge is highly recommended (Böröcz & Singh, 2016; Rouillard & Richmond, 2007).

Figure 1a: Cumulative distribution function (CDF) of RMS-values of time-domain vibration signals, leaf spring train (full and empty cargo) / Figure 1b: CDF kurtosis-values of time-domain vibration signals, leaf spring train (full and empty cargo) / Figure 1c: CDF RMS-values of time-domain vibration signals, air-ride truck (full and empty cargo) / Figure 1d: CDF kurtosis-values of time-domain vibration signals, air-ride truck (full and empty cargo)

Figure 1a

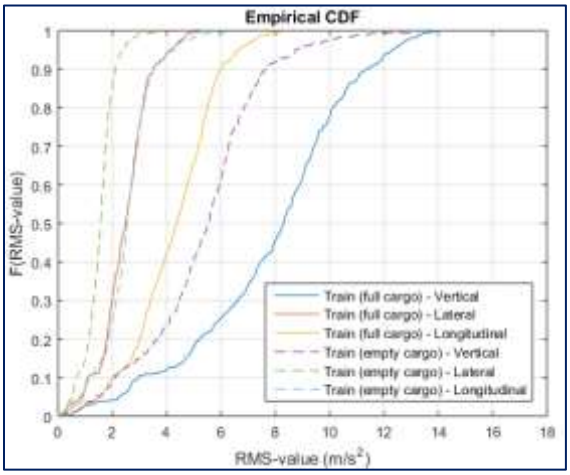



Figure 1b

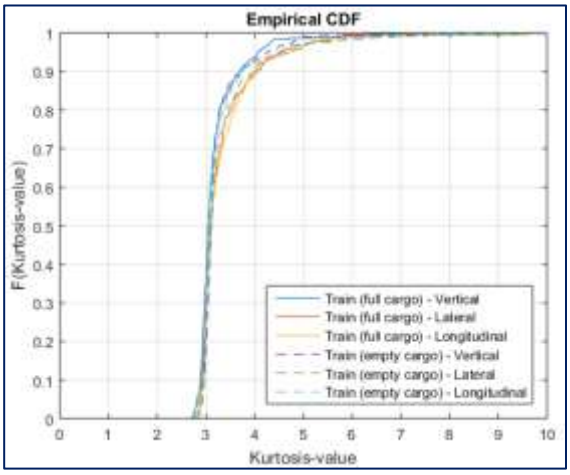



Figure 1c

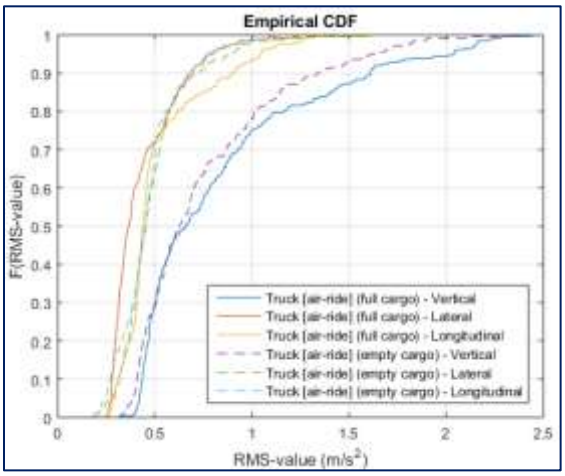
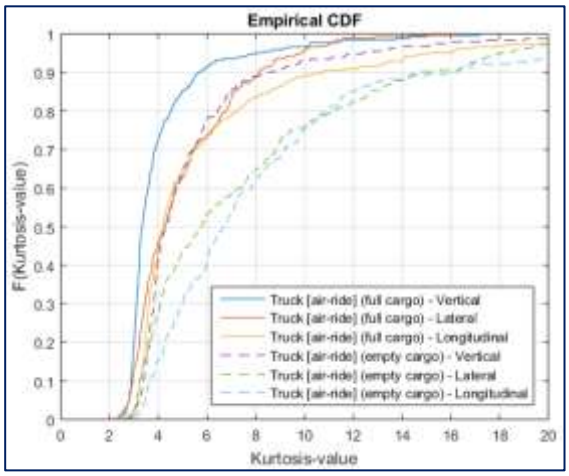



Figure 1d




Source: Own measurements

In order to validate the findings of this study, results were benchmarked with the international standards (ASTM D4169). Vibration measurements in both truck and train significantly differ from the standards, as is also suggested in literature (Böröcz & Singh, 2016; Chonhenchob et al., 2009; Garcia-Romeu-Martinez et al., 2008; Rissi et al., 2008). However, the spectral density plots of trucks described in literature are to a large extent similar to the results presented in this study (e.g. Garcia-Romeu-Martinez et al. (2008), Rissi et al. (2008), Singh et al. (2006), and Soleimani & Ahmadi (2014)). The vibration levels are most comparable with the study of Soleimani & Ahmadi (2014), since the accelerometers were mounted on the lowest crate/pallet to identify the influence of vibrations on food packages. The vibration levels identified by Rissi et al. (2008) measured during multiple truck transports in Brazil are to a lesser extent comparable since the data recorders were mounted on the undercarriage of the truck. Chonhenchob et al. (2009), Garcia-Romeu-Martinez et al. (2008) and Singh et al. (2006), which

have measured vibrations on the container surface, observe similar low-frequency vibrations (0.1-10 Hz) but lower high-frequency vibrations (10-100 Hz). In the study of Lu et al. (2010) vibration levels were ought to be considerably lower. In order to realistically simulate transport, the results suggest adaptations to the international standards as well as further improvements of the recommended test methods, such as ASTM D4728 and ISO 13355.

Figure 2a: PSD train transport (Vertical container/bogie measurements) / Figure 2b: PSD train transport (Container/bogie measurements) / Figure 2c: PSD (air-ride) truck transport (Vertical container floor measurements) / Figure 2d: PSD (air-ride) truck transport (Container floor measurements)

Figure 2a

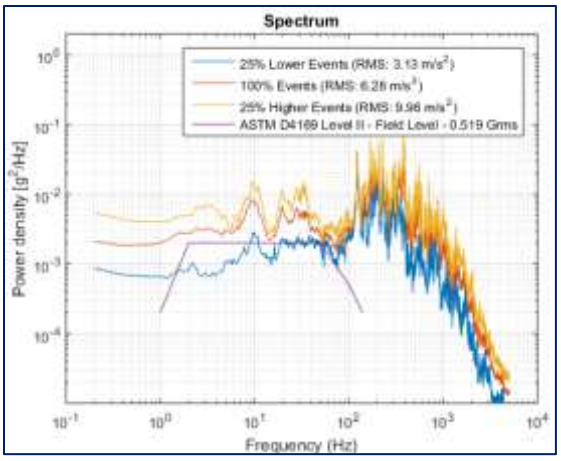



Figure 2b

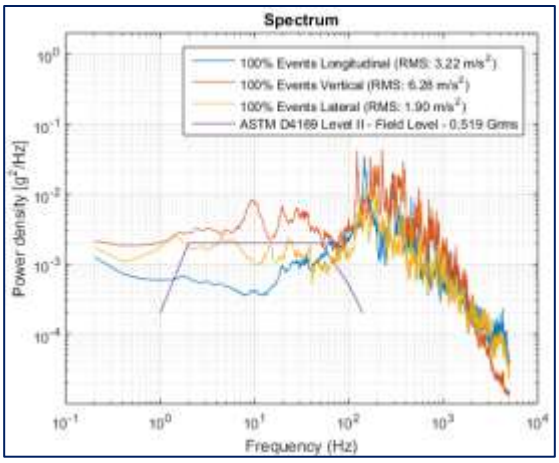



Figure 2c

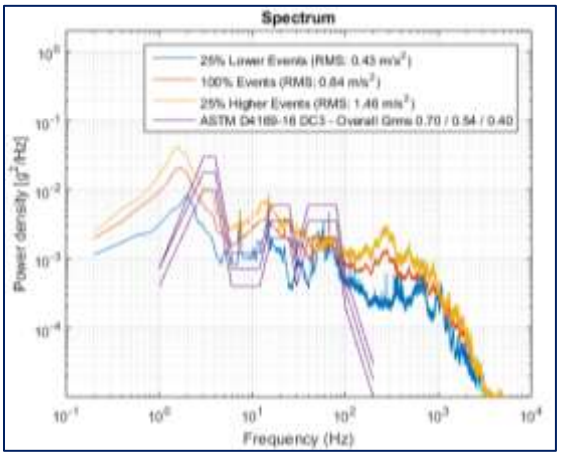
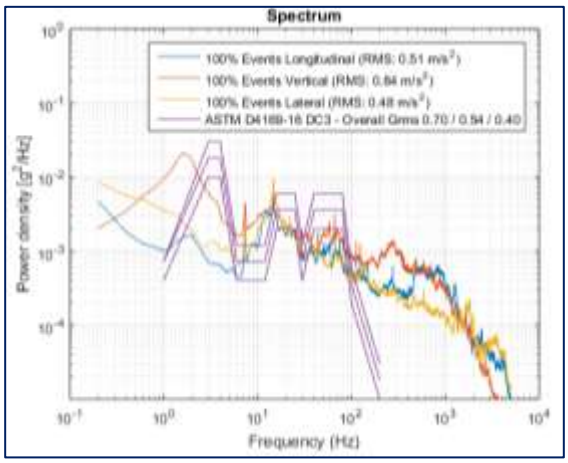



Figure 2d




Source: Own measurements

### *3.2 Shock analysis – train and truck transport*

In order to facilitate simulation testing, the complex shocks that occur during train and truck transport are analyzed as a decaying sinusoid. Thirty shocks in both air-ride truck and leaf-spring railcars were studied, as theoretically shown in Section 2 (Material & Methods). During truck transport the frequency of the damped oscillation ($\omega_d$) is on average 153 Hz ± 148 Hz. The damping ratio (β) over the different shocks is on average equal to the dimensionless number 0.08 ± 0.02, which means that the amplitude of the second peak is estimated to be 60 ± 8% of the amplitude of the first peak. With respect to train transport, the frequency of the damped

oscillation ($\omega_d$) is identified as 1559 Hz on average ± 1970 Hz. The damping ratio (β) of shocks measured on the railcar is on average 0.05 ± 0.02, which means that the amplitude of the second peak is estimated to be 73 ± 10% of the amplitude of the first peak. The large variance in the damping ratio and the frequency of the damped oscillation is predominantly attributed to the diversity in transient phenomena that occur during transport. This analysis suggests that shocks are more damped during truck transport than during railway transport. Furthermore, the frequency of the damped oscillation is higher during train transport than during truck transport, which is attributed to the complex dynamics and interactions of the couplers. Food scientists or packaging engineers can simulate transport shocks with using a free-fall device by artificially changing the damping ratio. In research, often a free-fall device or impact testing is used to simulate shocks to which products are exposed to (e.g. shocks on apples (Gołacki et al., 2009)). By adapting the design of shock simulation tests to the observed phenomena measured during transport, both a better validation of the design of the experiments and more representative results can be guaranteed.

### *3.3 Analysis of selected events – train and truck transport*

In Figures 3a-d, time-domain vibration plots of vibration and shock phenomena measured on a train transport are presented. Figure 4a illustrates the vibration pattern when the train accelerates. By accelerating after standing still, the tension of the couplers between the railcars is increased. The inverse phenomenon, in which tension between the railcars is lowered, occurs when braking or coming to a standstill after traveling. Therefore, similar shock phenomena are observed when accelerating after standing still and when stopping and coming to a standstill. The interaction of the couplers not only shapes the vibration spectra, it also adds complexity to the analysis of the measured vibrations and shocks. When traveling over a railway network, trains frequently have the possibility to change tracks. By passing track switches, the train is exposed to a shock of which the magnitude depends on the velocity of traveling. In a railway yard with multiple switches, multiple shocks of high magnitude are generated (although trains are required to decrease speed – Figure 3b). Also, trains that pass in the opposite direction can generate an elevation in the magnitude of the vibrations. In Figure 3c, vibration measurements were performed when standing still while a train passes in the opposite direction. Results indicate that the magnitude of the vibrations is elevated by approximately 1 $m/s^2$. When a train travels at full speed (approx. 90km/h), fewer shocks occur but the vibration level is significantly high. In Figure 3d, a histogram of the measured time-domain vibration samples higher than $5m/s^2$ was made with the objective to identify the number of shocks that occur per minute. The variation in transient phenomena also causes substantial confidence intervals of the histograms of the measured time-domain vibration samples. The latter histogram can be used by food scientist and packaging engineers to design experimental shock tests.

Different vibration and shock patterns are present during truck transport (air-spring suspension). Shocks of high amplitude are frequently measured during transport, which is caused by road unevenness, potholes or speed control humps. Research findings also indicate that start-stop moments in which the driver needs to brake or accelerate are not the main cause of the occurrence of shocks. However, during start-stop moments the truck is mostly located on or close to crossroads, which frequently induce a change in pavement type (with potholes or road unevenness). In Table 1, time-domain vibration and shock patterns when driving by truck over different Belgian road types are characterized. The road network is segmented by the speed

of traveling and road type to identify vibration and shock patterns when driving over the most common Belgian urban roads, secondary roads, and highways. The results are summarized as follows.

- *Asphalt roads (< 30 km/h)* induce the lowest RMS-values of the measured time-domain vibration signals (Avg. RMS-values of the vibration signals in time-domain over 1-second intervals: 0.14 $m/s^2$ ± 0.05 $m/s^2$). Nearly no shocks are observed when traveling over the specified road section. Furthermore, from the cumulative distribution function (CDF) of the RMS-values of the vibration signals in time-domain can be derived that longitudinal vibrations are of remarkable amplitude. The latter effect can be attributed to braking and acceleration of the truck, which is often unavoidable in road sections with the speed limit at 30 km/h.
- When driving over *cobblestones (< 30 km/h)*, vibration and shock patterns are most severe (Avg. RMS-values of the vibration signals in time-domain over 1-second intervals: 5.46 $m/s^2$ ± 1.94 $m/s^2$).
- *Asphalt roads (30-70 km/h)* induce lower RMS-values of the measured time-domain vibration signals than concrete pavement (30-70 km/h), since the average is 0.47 $m/s^2$ ± 0.14 $m/s^2$.
- Roads with *concrete pavement (30-70 km/h)* have average RMS-values of the vibration signals in time-domain of 1.32 $m/s^2$ ± 0.54 $m/s^2$. Shocks are more frequently observed when driving over concrete pavement (30-70 km/h) than when driving over asphalt roads (30-70 km/h and >70 km/h). Furthermore, when driving over concrete pavement lateral vibrations are more severe than compared to other pavement types and speed limits. The latter effect can be attributed to road unevenness, which is inherent to the pavement type. For instance, broken concrete pavement can induce left or right truck wheels to generate vibrations of different or higher amplitude. Similar vibration patterns that generate lateral vibrations can be found when driving over metal joints, as observed by Lu et al. (2008).
- Highways, i.e. *asphalt roads (> 70 km/h)*, can be characterized by RMS-values of the vibration signals in time-domain of highways with average of 0.77 $m/s^2$ ± 0.21 $m/s^2$.

Figure 3a: Vibrations in time-domain (train starts and accelerates) / Figure 3b: Vibrations in time-domain (train switches on a railway yard) / Figure 3c: Vibrations in time-domain (passing of a train while standing still) / Figure 3d: Histogram of peaks (> 5 m/s$^2$) during train transport

Figure 3a

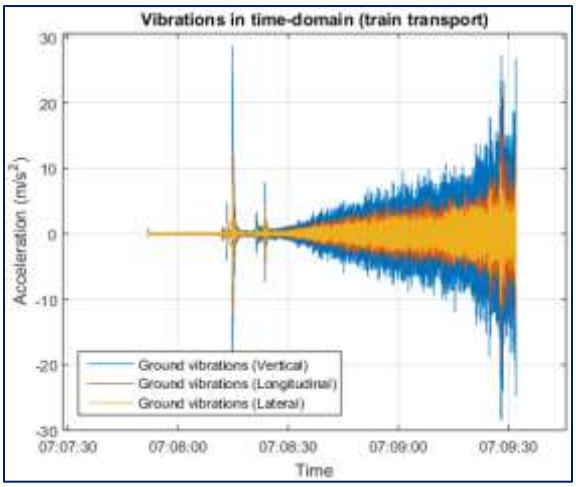



Figure 3b

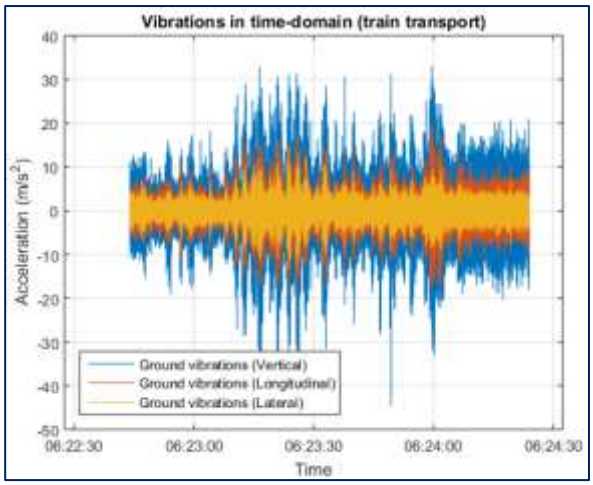



Figure 3c

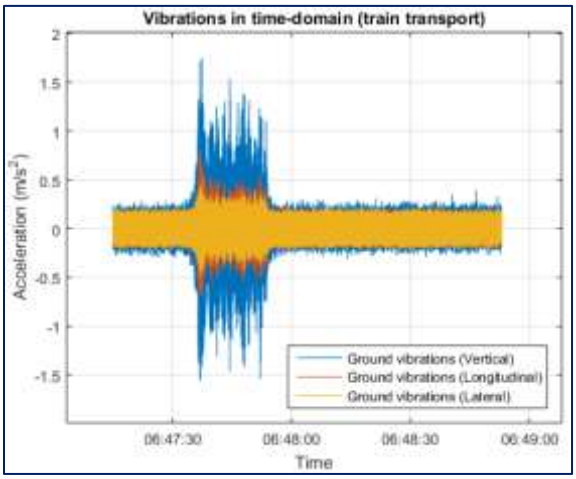
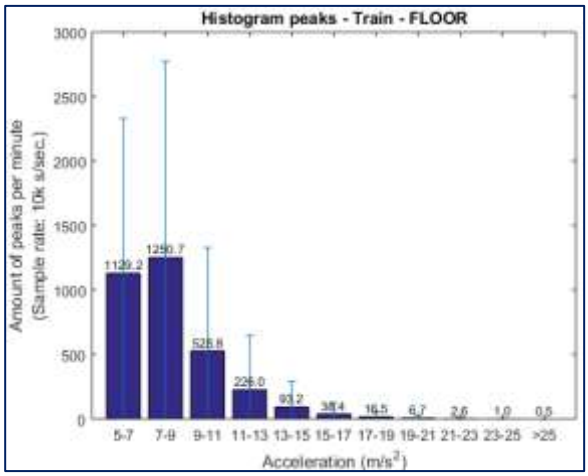



Figure 3d




Source: Own measurements

### *3.4 Discussion on the design of transport simulations and experiments with respect to food products*

Literature reports of different food products that suffer from quality deterioration during transport. Wasala, Dharmasena, Dissanayake, & Thilakarathne (2015) indicate that between 20-30% of the initial harvested bananas is allocated to waste due to transport vibrations and shocks (study conducted in Sri Lanka). Also, kiwis (Tabatabaekoloor, Hashemi, & Taghizade, 2013), watermelons (Shahbazi, Rajabipour, Mohtasebi, & Rafie, 2010), tangerines (Jarimopas, Singh, & Saengnil, 2005), eggs (Berardinelli, Donati, Giunchi, Guarnieri, & Ragni, 2003), strawberries (La Scalia et al., 2015) and grapes (Fischer, Craig, & Ashby, 1990) face similar problems. A recent study even reports the sensitivity of beer, i.e. the formation of haze, to transport vibrations (Janssen et al., 2014). The largest and most developed research domain with respect to the current topic is the losses of apples due to postharvest transportation (Acıcan, Alibaş, & Özelkök, 2007; Gołacki, Rowiński, & Stropek, 2009; Van Zeebroeck et al., 2007).

According to recent estimates, a loss rate between approximately 10% and 25% is typically measured in industry (study conducted in Belgium) (Van Zeebroeck et al., 2007). The loss rate is attributed to the appearance of bruises, but also the presence of minor mechanical injuries (punctures, cuts, and abrasions) can later on lead to fungal diseases. Postharvest pathogens such as gray mold (Botrytis) or blue mold (Penicillium) are able to enter the fruit by the dead or wounded tissue and can contaminate the rest of the fruit. Vibrations and shocks occurring during transports are a major contributor to these bruises and punctures on apples, and, as a consequence, need to be avoided (Van Zeebroeck et al., 2007).

Food scientists employed different designs of experiments to simulate transport, to estimate the food losses or the damage to fruits, and the importance of different variables (e.g. apple species). Chonhenchob et al. (2009) and Jarimopas et al. (2005) performed an actual food transport, measured the vibrations, and visually inspected the quality damage to the food products. The current methodology is the most accurate in identifying the damage to fruits, however also lacks the feasibility to adapt the experimental variables (e.g. temperature). Therefore, transport simulations in a dedicated and controlled environment in which repeated experiments can be executed better identify research findings. However, most of the experimental studies focus only on vibrations without investigating the impact of transient vibrations or shocks and, therefore, are incomplete, e.g. Berardinelli et al. (2003), La Scalia et al. (2015), Wasala et al. (2015). Other studies, such as Acıcan et al. (2007) and Gołacki et al. (2009) performed a free fall test of individual apples, respectively a crate of apples, of the drop height of 5 cm, respectively 30 cm, without benchmarking the drop height with shock results during transport. The current study can fill this research gap with providing accurate data, and a methodology to develop a streamlined and benchmarked design of vibration and shock experiments in order to simulate transports.

The researchers of the current study are aware that food scientists are dependent on the vibration equipment that can be adopted for their experimental research. Predominantly shakers that can generate vibrations in a single dimension are adopted by food scientistsII and, therefore, the developed procedure of transport simulations is based on the latter insight.

- In an initial phase, the transmissibility of the vibrations between the wooden pallet and the highest stacked food packages should be studied. This can be performed in a transport setting (Soleimani & Ahmadi, 2014) or in a simulation setting (La Scalia et al., 2015). This explorative experiment is recommended since vibrations in the highest stacked crates can be attenuated due to the stacking (O'Brien, Gentry, & Gibson, 1965).
- Consecutively, the individual impact of vibrations on the quality of the food product should be studied. Moreover, the effect of individual frequencies (Fischer, Craig, & Ashby, 1990) or, if possible, the effect of different PSDs (Berardinelli, Donati, Giunchi, Guarnieri, & Ragni, 2003) should be derived. For instance, an extreme vertical vibration of 1.5 $m/s^2$ (RMS – Table 1) that was observed during truck transport over asphalt pavement (> 70 km/h) can be imposed.
- In a dedicated shock test, the effect of transient vibrations on the quality of the food product should be identified. A free fall test should be designed in which the drop height and the material of the ground surface should be iteratively identified by measuring the acceleration on the food package. As a consequence, the damping ratio and the

[II] Shaking in the vertical dimension is recommended due to higher amplitude of the vertical relative to the lateral and longitudinal vibrations in transport (Figure 1a and 1c).

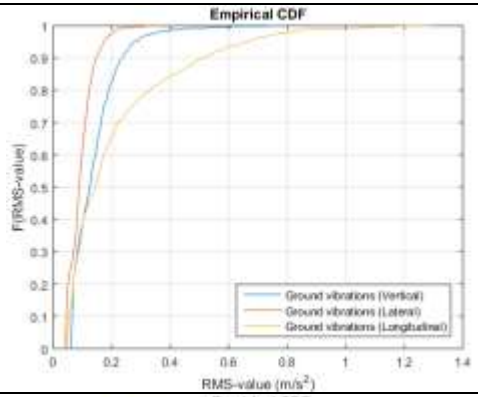
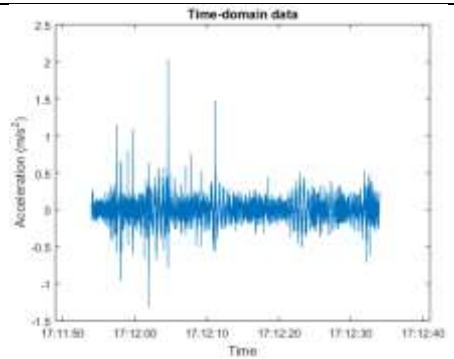
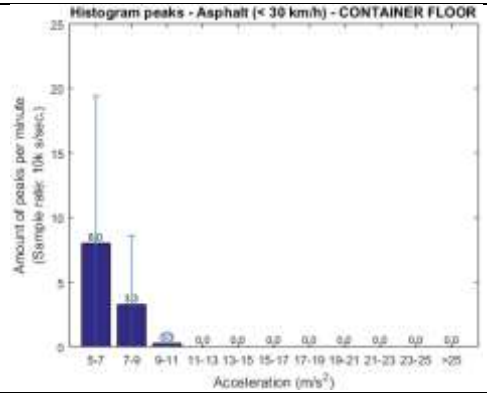
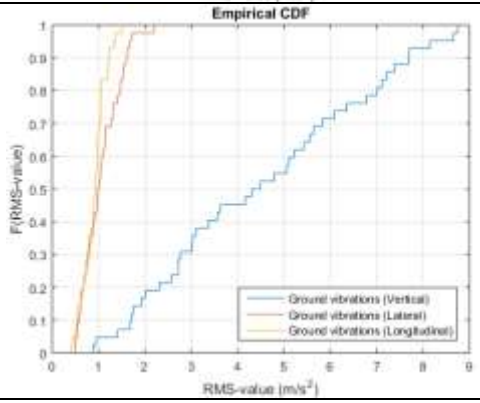
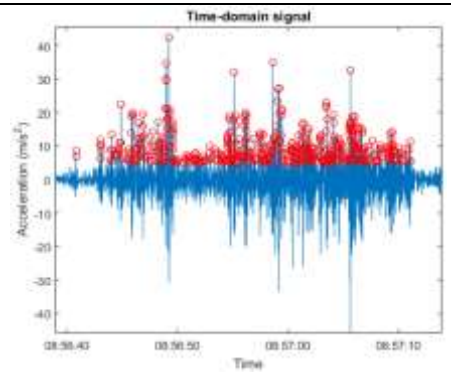
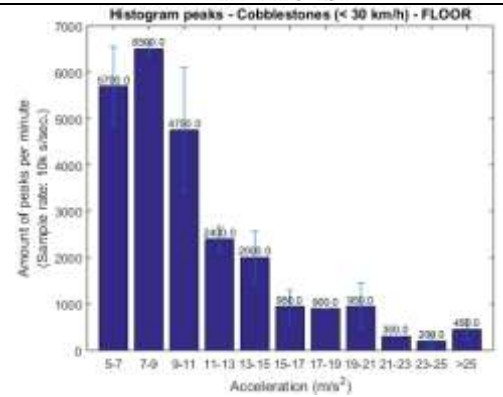
frequency of the damped oscillation that is observed during transport can be approximatedIII. From the results in Table 1, an input signal can be selected. For instance, when simulating shocks during truck transport over asphalt pavement (> 70 km/h) 8 shocks per minute with a peak acceleration of approx. 10 ± 1 $m/s^2$ should be imposed, 3 shocks per minute of approx. 12 ± 1 $m/s^2$, and 1 shocks per minute of approx. 14 ± 1 $m/s^2$. The samples of a smaller amplitude (acceleration bins) are considered the damping phenomena and are not imposed as individual shocks.

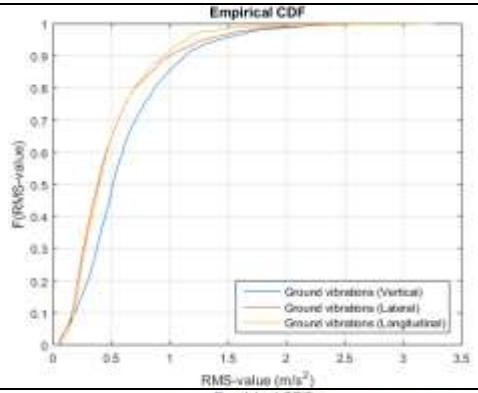
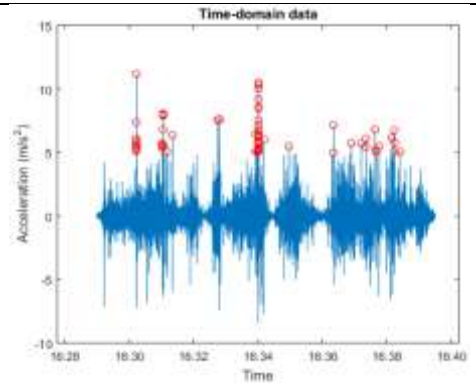
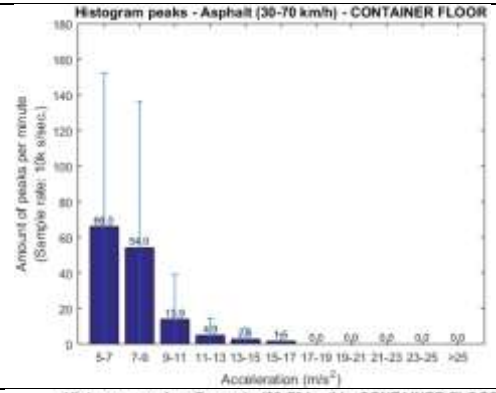
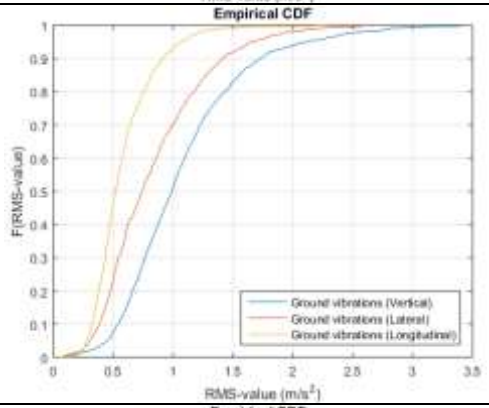
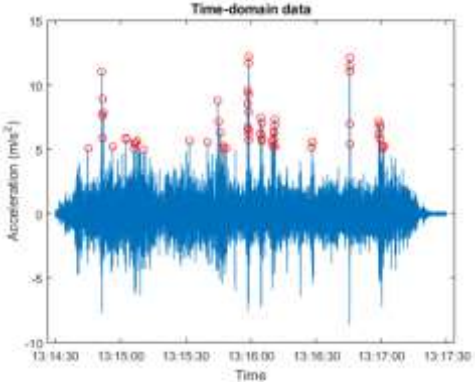
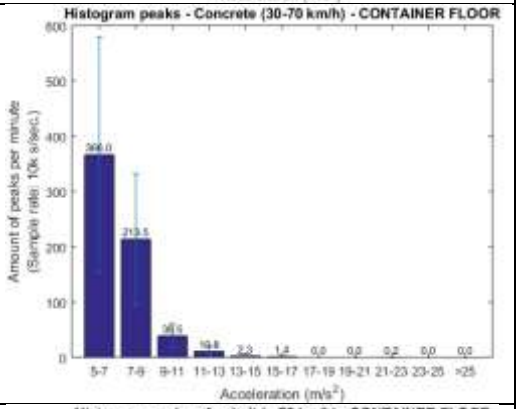
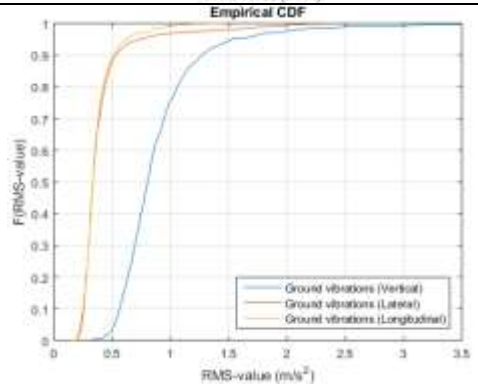
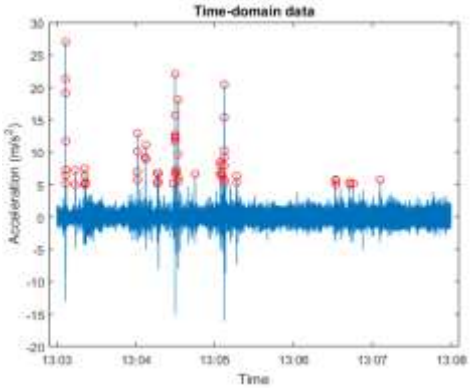
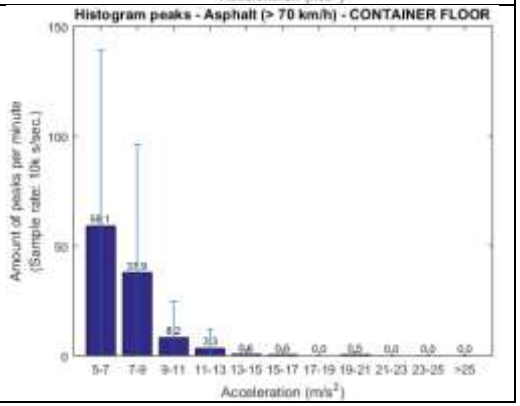
- In a last experiment, the food product should be sequentially exposed to vibrations and shocks (e.g. cycles with 20 min of vibrations and 10 min. of shocks). Since the measurements of the current paper identify the frequency of the transient vibrations that occur during transport (i.e. the number of shocks per minute of traversed road), the same shock pattern can be simulated. The reason for imposing both vibrations and shocks in one experiment is the possible multiplicative harmful effect on the food product. For example, shocks could cause punctures, cuts and abrasions on apples, which could provoke the vibrations to generate additional damage.

A vibration test in which the food product is exposed to both vibrations and shocks will produce more reliable results with respect to food losses, mechanical damage or decrease in quality. Additionally, the significance of the effect of the investigated parameters (e.g. apple type, temperature) is better determined since a more realistic transport simulation is performed. Furthermore, the findings in Table 1 provides the food scientist data that make able to simulate transport over different road segments comparable with real-life transport.

[III] The drop height is dependent on the mass as well as the packaging material of the food package. Therefore, no fixed drop height can be recommended to food scientists.

Table 1: Characterization of Belgian roads (vibration response; truck with air-ride suspension)

| Road surface (speed segmentation) | Cumulative distribution function (CDF) of RMS-value – acceleration of time-domain vibrations [Vertical; intervals of 1s] | Peaks in acceleration (> 5 m/s$^2$) – Time-domain – [Example] | Shocks: Histogram of time-domain vibration samples (> 5 m/s$^2$) – Peak – |
|---|---|---|---|
| Asphalt pavement (< 30 km/h)  Source: ("Asphalt pavement pic1" 2016) |   |   |   |
| Cobblestones (< 30 km/h)  Source: ("Cobblestones pic", 2016) |   |   |   |

| | | | |
|---|---|---|---|
| Asphalt pavement (30-70 km/h)<br>  <br>Source: (“Asphalt pavement pic2”, 2016) |  |  |  |
| Concrete pavement (30-70 km/h)<br>  <br>Source: (“Concrete pavement pic”, 2016) |  |  |  |
| Asphalt pavement (> 70 km/h)<br>  <br>Source: (“Asphalt pavement pic3”, 2016) |  |  |  |

## 4. Conclusions

From the Fourier spectra reported in this study, and the extensive time-domain analysis of the measured vibration and shock patterns that are present when traveling over the Belgian road and railway network, the following main conclusions are deduced.

- Transient phenomena frequently occur in both truck and train transport, which cannot be observed or derived from the averaged PSD plots. A time-domain event analysis indicated that railcars are exposed to shock phenomena when riding over switches in a railway yard, accelerating after standing still and coming to a standstill after braking. During truck transport, road unevenness has a significant impact on the measured vibrations and shocks. Traveling over cobblestones, and concrete pavement generates the most severe RMS-vibrations and shocks. The dependency of vibrations, shocks and the velocity of the truck is also illustrated.
- The damping ratio (β) of shocks measured in the container of the truck and on the railcar is on average 0.08 ± 0.02, respectively 0.05 ± 0.02 (frequency of the damped oscillation 153 ± 148 Hz, respectively 1559 ± 1970 Hz). By artificially adapting the impact and, as a consequence, better approximating the damping ratio and the frequency of the damped oscillation when executing drop tests, food scientists can realistically simulate transient phenomena that occur during transport.

The authors of the current research suggest the research domain to also report on shocks that occur during transport. Furthermore, in future research, food scientists and package engineers can use the insights of this paper to perform advanced simulation testing incorporating both vibrations and shocks. A better design of the simulation test will allow products to be tested on the extreme levels of vibrations and shocks they are exposed to during transport. The streamlined method developed in the current study will result in more reliable results with respect to food losses and food damage, and a better identification of the significance of the tested parameters.

APPENDIX

**Specifications vibration measurements (truck):** Transport 1: truck + trailer 3 axles (1+2) [MAN TGA SH265 FNLC] (length trailer 7.5 meters – weight full capacity 26 tons – end of transport 15 tons) – extra trailer 2 axles [Renders RMAC 9.9N] (length trailer 7.5 meters – weight full capacity 18 tons – end of transport 13.5 tons) // Transport 2: truck + trailer 3 axles (1+2) [MAN TGA SH265 FNLC] (length trailer 7.5 meters – weight full capacity 26 tons – end of transport 15 tons) // Transport 3: truck + trailer 5 axles (2+3) [Volvo FH440 + Renders Liftachse ROC 12.27N] (length trailer 13.5 meters – weight full capacity 39 tons – end of transport 16 tons) // Transport 4: truck + trailer 5 axles (2+3) [VOLVO FH440 + Renders Liftachse ROC 12.27N] (length trailer 13.5 meters – weight full capacity 39 tons – end of transport 16 tons).

The authors of current research had the objective to measure the most extreme vibrations. Therefore, the measuring devices were located on top of a wooden pallet between one forth and one third of the rear end of the (extra) trailer length (respectively 1.8m - 2.5m [transport 1], 1.8m - 2.5m [transport 2], 3m – 4.5m [transport 3 and 4]).

Close to all food products are transported in their (secondary) packaging and stacked on pallets. Therefore, vibrations were measured on top of the wooden pallet itself (exactly the same spot for all case studies) in order to identify the vibrations packages are subjected to and to incorporate the resultant of the (possible) interaction between the pallet and the container floor. The vibration measurements performed in current research are used to simulate transport and, therefore, it is worthwhile to incorporate the (possible) effect of the pallet.

**Specifications vibration measurements (train):** Railcar: Max. 90 tons (of which 24 tons cargo), In total 15-25 wagons

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