Measurement and analysis of vibration and shock levels for truck transport in Belgium with respect to packaged beer during transit

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ABSTRACT (150 words)

Temperature, vibrations and shocks during transport and storage are believed responsible for beer flavour instability. The aim of current study is twofold: (1) to quantify the vibrations and shocks on packaged bottled beer when travelling on the Belgian road network, (2) quantify the impact of the vibrations and shocks in a preliminary experiment.

The spectral density plots illustrate the importance of low-frequency vibrations and the similarities/discrepancies with international standards (ASTM-D4728 and ISO-13355). With increasing stack height, the amplitude of vibrations (5-25Hz) intensifies in both corrugated boxes and plastic crates. Vibrations >25Hz are amplified up to 9 times the original signal depending on the stack height of plastic crates. Corrugated boxes attenuate vibrations >25Hz. Corrugated boxes absorb shocks and are preferred over plastic crates with respect to shocks and vibrations. In an exploratory experiment, vibrations and shocks induce the uptake of oxygen and the change of aldehydes (dependency initial oxygen content).

Keywords

Vibrations, shocks, beer packaging, quality degradation, transmissibility curve

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1. Introduction

Postharvest losses of fruit and vegetables, defined as the losses occurring during transport, handling and storage before the food product reaches the consumer, can be as high as 25% of the initial harvested or produced products (Parfitt, Barthel, & Macnaughton, 2010; Van Zeebroeck et al., 2007; Wasala, Dharmasena, Dissanayake, & Thilakarathne, 2015). In the literature, extensive research was done on fruit losses due to vibrations during truck transport (e.g. losses of apples (Van Zeebroeck et al., 2007), pears (Zhou, Su, Yan, & Li, 2007), tangerines (Jarimopas, Singh, & Saengnil, 2005), etc.). Vibrations and shocks, caused by road unevenness and potholes, can directly induce mechanical damage to the products (Lu, Ishikawa, Shiina, & Satake, 2008). In recent studies, researchers also highlighted that a transport load can deteriorate in quality, i.e. changes in the chemical composition of the product, due to vibrations and shocks. An example of the latter phenomenon can be found in the transport of strawberries (Fischer, Craig, & Ashby, 1990; La Scalia et al., 2015). The decline in the sensorial quality of beer during storage was illustrated by several authors (Vanderhaegen, Neven, Verachtert, & Derdelinckx, 2006; Vanderhaegen, Delvaux, Daenen, Verachtert, & Delvaux, 2007). In this paper, the focus is on the identification of transport vibrations and shocks occurring during beer transports, since literature indicated that a decrease in beer quality might also occur during transport (Janssen et al., 2014). However, also more general findings and recommendations regarding packaging materials can be deduced from the findings of this research and extrapolated for food, beverage and electronic products (which is also susceptible to vibration damage). In this regard, under-packaging or the lack of adequate and sufficient packaging to protect a product from damaging, but also over-packaging products should be avoided. Recent estimates indicate that the total cost of over-packaging for all products, in Europe alone, compasses 130 billion per year (Rouillard & Richmond, 2007).

Since beer is increasingly exported, due to market globalization, more often the beverage is subject to longer transportation times and variable storage conditions that lead to an unfavorable decrease in beer flavor (Vanderhaegen et al., 2007). During transport, bottled beer is being exposed to changing temperatures, vibrations and shocks, which may influence the flavor stability. Janssen et al. (2014) signaled that vibrations during transport influence the development of turbidity in beer. However, the exact influence of vibrations and shocks on the beer quality is a research gap that needs to be explored. A first step to perform this research is to identify the (level of) vibrations that occur during beer transports, and this will be the topic of this paper. Consecutively, with improving the quality of beer, the aim is to contribute to a longer shelf life of the beverage as well as an increased customer experience. Similarly to other food products and beverages, it is desirable to extend the shelf life. On the one hand, direct losses due to mechanical damage can be reduced. On the other hand, the quality of the products will directly induce a longer period in which the product can be consumed or, in other words, a longer shelf life of the product.

In literature, vibration levels during truck transport have been studied worldwide: Japan (Lu et al., 2008), Thailand (Jarimopas et al., 2005), Spain (Garcia-Romeu-Martinez, Singh & Cloquell-Ballester, 2008), and multiple other countries (Chonhenchob, Singh, Singh, Stallings, & Grewal, 2012; Rissi, Singh, Burgess, & Singh, 2008; Singh, Singh, & Joneson, 2006; Singh, Jarimopas, & Saengnil, 2006). These publications present a diverse set of parameters that could indicate the origin or the amplifying effects that influence the generated vibrations. Road roughness and speed of driving during transportation are important vibration parameters (Jarimopas et al., 2005; Lu et al., 2008). Jarimopas et al. (2005), for instance, illustrated vibration performance over a diverse set of pavement surfaces. The truck type, payload, and suspension are also relevant parameters. Garcia-Romeu-Martinez et al. (2008) indicated that root mean square (RMS) and peak vibration can be reduced by 50% by using a truck with an air-ride suspension over a leaf-spring suspension. Other relevant parameters that influence vibration levels are platform location (Zhou et al., 2007), vibration direction (Singh, Antle, & Burgess, 1992) and tires (Jones, Holt, & Schoorl, 1991).

The aim of the current work was to identify the level of vibrations and shocks bottled beer is subjected to when transporting by truck, and using different packaging modalities, and, additionally, to assess the impact of vibrations and shocks on the beer flavor quality (case-study). There are three transport modes that are regularly used to transport beer: trucks, trains, and ships. The scope of this paper was limited to vibration analysis of truck transport (leaf spring and air-ride suspension) in Belgium. Research on truck vibrations is extensive and has expanded considerably in last years. However, the relation between vibrations and shocks during transport with product packaging is often missing or underdeveloped in literature (Eissa, Gamaa, Gomaa, & Azam, 2012). This emphasizes the unique contribution of this paper. The current research was also limited to bottled beer stacked on top of each other in cardboard boxes and plastic crates, the two most commonly used packaging modalities for beer. Plastic crates are frequently used for domestic transportation, due to the recycling logistics of the crates, while cardboard boxes are especially used for transports to foreign countries. Furthermore, the transmissibility of the pallet vibrations to the highest stacked crates is identified and, therefore, the insights of the interaction between vibrations and bottled beer could be extended to other geographical regions by changing the (input) vibration spectra or the amplitude of the vibrations. Bottled beverages that suffer quality deterioration (for instance wine (Chung, Son, Park, Kim, & Lim, 2008)), or other food products (for instance strawberries (Fischer et al., 1990)) could use these findings to further develop their research study.

2. Materials and methods

2.1 EXPERIMENTAL DESIGN

For the purpose of this research, vibration measurements were performed on four (beer) transports, three transports with an air-ride suspension truck and one truck transport with a leaf spring suspension. All truck transports were executed over the Belgian road infrastructure. The road typology in Belgium can be categorized as national highways, highways and local or rural roads. Highways are major roads that connect districts and large cities and make able to transport freight over medium and long distances. In current study, the Belgian national highways that were studied are predominantly paved with asphalt. The highways are paved both by asphalt and by concrete, while rural roads are predominantly paved by asphalt but exceptionally by cobblestones. Since attention was given on the validity and significance, the presented results are findings from traveling by truck over all different roads and measured on four different transports.

Table 1 presents an overview of the transports that were attended by the author of this study. The number of transports made able to benchmark and validate the results. As an experimental set-up, plastic crates, as well as cardboard boxes, were stacked on top of each other (5-7 boxes/crates on top of each other). Three accelerometers were used: one accelerometer was mounted on the floor of the container (on top of the wooden pallet), and two accelerometers on the bottleneck of two beer bottles (Figure 1a) that were located in the stacked crates or boxes (Figure 1b and 1c). In order to not influence the interaction between the bottle and the packaging, the accelerometers were mounted on the beer bottleneck. Since food products are transported on wooden pallets, vibrations were measured on the pallet itself and not on the container floor. The aim was to discover the transmissibility of the pallet vibrations to the vibrations beer bottles are exposed to in their beer packaging. During all transports, a camera (GoPro Hero 4) was mounted on the seat of the truck driver to visually capture the road characteristics and the driving speed. Vibrations measurements were performed during transports with full, empty and varying cargo load.

Figure 1a: Accelerometer mounted on the beer bottleneck
Figure 1b: Plastic crates stacked on top of each other
Figure 1c: Corrugated boxes stacked on top of each other

Figure 1a

Figure 1b

Figure 1c

Source: Own content

Table 1: Overview transports – vibrations measurements

<table>
<tr><td>TRANSPORT (Recording time)</td><td>TYPE OF TRANSPORT</td><td>ACCELEROMETERS</td><td>EXPERIMENTAL SET-UP</td></tr>
<tr><td>* Beer Transport 1 (Rec.time: 9hrs 44mins)</td><td>Truck transport (trailer with extra trailer with air-ride suspension) [Specifications Appendix (1)]</td><td rowspan="4">Acc 1: on top of a wooden pallet
Acc 2: bottle neck of a bottle in lowest plastic crate / cardboard crate
Acc 3: bottle neck of a bottle in highest plastic crate / cardboard crate

[Specifications Appendix (2)]</td><td>Plastic crates stacked on top of each other</td></tr>
<tr><td>* Beer Transport 2 (Rec.time: 2hrs 28mins)</td><td>Truck transport (trailer with air-ride suspension) [Specifications Appendix (1)]</td><td>Plastic crates and cardboard boxes stacked on top of each other</td></tr>
<tr><td>* Beer Transport 3 (Rec.time: 1hrs 50mins)</td><td>Truck transport (trailer with air-ride suspension) [Specifications Appendix (1)]</td><td>Plastic crates and cardboard boxes stacked on top of each other</td></tr>
<tr><td>* Beer Transport 4 (Rec.time: 3hrs 26mins)</td><td>Truck transport (trailer with leaf spring suspension) [Specifications Appendix (1)]</td><td>Cardboard boxes stacked on top of each other</td></tr>
</table>

In order to quantify the vibration response during beer transports, vibration measurements were performed with the following experimental set-up. A laptop was connected to a data acquisition board (National Instruments USB-6361), which was connected to different accelerometers. The accelerometers (Sparkfun ADXL 337), mounted on the pallet and on the beer bottlenecks, measured acceleration in three directions. Most research articles on vibrations during transport analyze vibrations up to 100 Hz (Berardinelli, Donati, Giunchi, Guarnieri, & Ragni, 2003;

Jarimopas et al., 2005), in this study the Nyquist-frequency was fixed sufficiently higher to also evaluate the influence of high-frequency vibrations. The accelerometers, which have a bandwidth of 1600 Hz (X- and Y-axis / noise density: 175 μg/√Hz rms) and 550 Hz (Z-axis / noise density: 300 μg/√Hz rms), had a sample rate of 1e5 samples per second. The total set-up was powered by an external battery and transformed to the necessary voltage using a transformer (Voltcraft SWD-300/12).

2.2 DATA ANALYSIS

The software Matlab R2015a was used to control the data acquisition board and to save the vibration data. The same software was employed to analyze the vibration signals. The cumulative distribution function (CDF) of the RMS and kurtosis values for different vibration segments over five second intervals were calculated. Kurtosis is a way to indicate the shape or the 'tailedness' of the probability distribution of the measured vibrations compared to the standard normal distribution (Böröcz & Singh, 2016). A kurtosis value of zero can be attributed to the standard normal distribution, while a heavy-tailed distribution is indicated by a positive kurtosis and light-tailed distribution by a negative kurtosis. Furthermore, a Fourier transform was performed and an estimation of the transmissibility function from pallet to the beer bottle neck was calculated. The acceleration transmissibility function is a function that presents the vibration attenuation and vibration amplification between two measured vibration signals in the frequency domain (Harris & Piersol, 2002). The function (g^2/g^2) is calculated by dividing the Fourier transform of the measured accelerations of the first accelerometer by the Fourier transform of the accelerations measured by the second accelerometer. The results of Section 3 indicate average power spectral density (PSD) plots, which are linear averages for PSDs for selected events (bandwidth / frequency resolution 0.2 Hz). There was no filter applied to the signals. The latter technique is frequently used in literature (Garcia-Romeu-Martinez et al., 2008).

Finally, a shock analysis was performed to evaluate both the number and the type of shocks packaged beer is subjected to. In current research, the measured vibration signals (in time-domain) were split into intervals of 20 seconds. Based on the measured vibrations and shocks in all intervals, a histogram was calculated to depict the amount of vibration samples that were measured above 5 m/s^2 (peak). A histogram of the acceleration samples above 5 m/s^2 was calculated for the signals measured on the pallet floor, as well as the signals measured on the stacked crates and boxes using exactly the same intervals. As a consequence, the different histograms can be compared and an indication of the number of shocks bottled beer is exposed to can be identified. The histograms reveal the average counts of vibrations samples (> 5 m/s^2) measured during transport with confidence boundaries (standard deviation up/down). Furthermore, individual shocks measured on the pallet, bottles in the highest corrugated box and plastic crate (20 shocks per setup) were analyzed in order to identify the type of shocks beer is exposed to. Since the measured shocks are best represented by a decaying sinusoid, the damping ratio (β) was identified. The damping ratio is a function of the logarithmic decrement (λ), the frequency of the damped oscillation (ω_d) and the damped period (T_d) (Thomson, 1993). The damped period is defined by the time between the two highest consecutive peaks. The logarithmic decrement can be calculated by 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 ($x(T_1 + T_d)$. Furthermore, the natural frequency of the damped oscillation (ω_n) can be computed (Thomson, 1993).

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

with

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

3. Results & Discussion

3.1 PALLET VIBRATIONS

Both vibrations and shocks of high amplitude are usually present during truck transport. Vibrations during transport mainly come from the engine, and the interplay between the road (road roughness), the tires and type of suspension. In literature, vibrations of low-frequency content are seen as considerably more important than high-frequency vibrations. In a typical PSD plot frequencies between 1-5 Hz are attributed to the suspension, 15-20 Hz the tires and 40-55 Hz the structure floor (Singh et al., 2006). The spectral density plots of the truck with air-ride suspension are displayed in Figures 2a and b. The spectral density plots indicate the importance of low-frequency vibrations. Furthermore, the plots also reveal the higher significance of vertical vibrations in comparison with longitudinal and lateral vibrations.

The PSD results were benchmarked with the in 2016 adapted international standards, i.e. ASTM D4169, and were found to be slightly different. However, similar findings, as the PSD (and RMS) results presented in this research, were found by other authors (e.g. Garcia-Romeu-Martinez et al. (2008), Singh et al. (2006), Soleimani & Ahmadi (2014) and Rissi et al. (2008)). In the research of Soleimani & Ahmadi (2014) the accelerometers were mounted on the lowest crate/pallet (and a stacking of crates) to identify the influence of vibrations on food packages. Therefore, the latter study was used to validate the findings in this experimental study. In the studies of Chonhenchob et al. (2009), Garcia-Romeu-Martinez et al. (2008) and Singh et al. (2006) the vibrations between 0.1 and 10 Hz have a similar amplitude, while the vibrations between 10 and 100 Hz were observed to be smaller. The latter authors, as well as Lu, Ishikawa, Kitazawa, & Satake, (2010) have mounted their data recorders on the container floor. The amplitude of the vibrations measured by Lu et al. (2010), on the contrary, is considerably smaller. The findings of Rissi et al. (2008) are similar, although the results should be compared with caution since in this study the data recorders were mounted on the undercarriage of the truck. To conclude, while current experimental study reports highly comparable PSD levels between 0.1 and 10 Hz, PSD levels between 10 and 100 Hz are higher than literature findings. However, PSD levels of vibrations on Belgian roads measured in current study are more comparable to ASTM D4169-16 DC3 than the results reported in literature. As indicated in the diverse plots and by diverse authors, the results suggest the need for further adaptations to the existing international standards (ASTM D4169) in order to develop improved recommended test methods, such as ASTM D4728 and ISO 13355.

Figure 2a: PSD (air-ride) truck transport (Vertical pallet measurements)
Figure 2b: PSD (air-ride) truck transport (Longitudinal, vertical and lateral pallet measurements)

Figure 2a

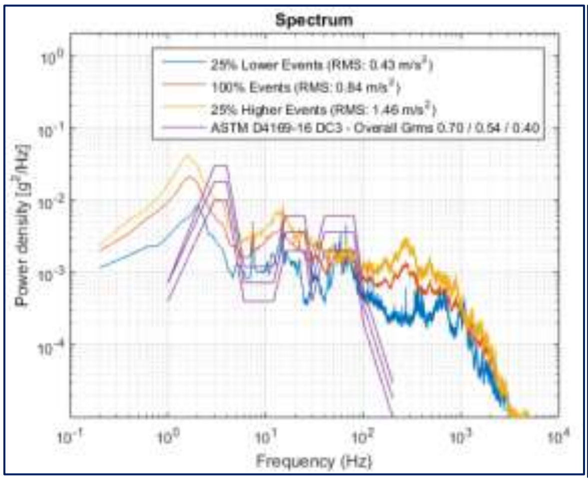
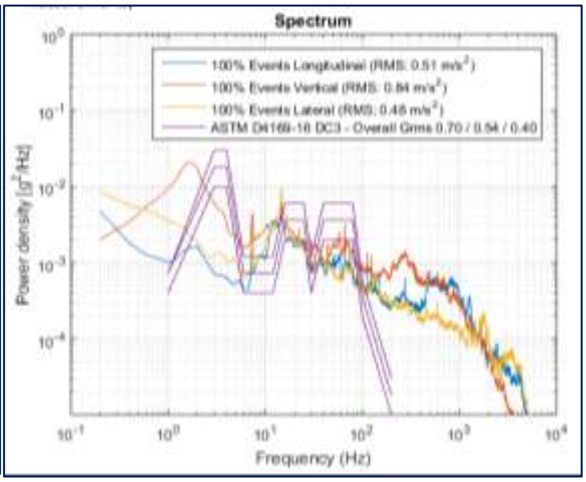


Figure 2b



Source: Own measurements

3.2 VIBRATIONS AND BEER PACKAGING

Figures 3a-d present the cumulative distribution function of the RMS and the kurtosis values of the measured acceleration signals (in time-domain) during the different transports. The RMS and kurtosis values of the pallet vibrations, as well as the vibrations beer is exposed to when stacking boxes or cardboard crates, are illustrated. The vibrations were measured in vertical (up-down), lateral (left-right) and longitudinal (back-forth) as displayed in the figures. However, the directions may diverge slightly over the different CDF-plots due to the attachment of the accelerometer to the pallet or slight movement of the beer bottle on which the accelerometer was mounted. Nevertheless, since the experimental design (stacking patterns, the stacking number, the sensors and the crates used) remained the same over all transports, the authors of current research results were able to validate the results. From Figures 3a and c can be concluded that the vertical vibrations are the most severe or have the highest RMS-values. The vibrations of the leaf spring trailer have a larger amplitude than the air-ride trailer. This was also found by diverse other authors (Garcia-Romeu-Martinez et al., 2008; Rissi et al., 2008). From the kurtosis plots (Figures 3b and d), can be concluded that predominantly a positive kurtosis is present during the transports. A probability density function with a positive kurtosis has more and more extreme outliers than the normal distribution. As a consequence, positive kurtosis indicates a strong dissociation between the induced vibrations and shocks. The frequent occurrence of shocks of high amplitude causes the heavy-tailed distribution. Due to the frequent occurrence of shocks during leaf spring truck transport, in extreme cases a significantly high kurtosis was measured (Figure 3d).

Figure 3a: CDF RMS-values of time-domain vibrations, air-ride truck
Figure 3b: CDF Kurtosis-values of time-domain vibrations, air-ride truck
Figure 3c: CDF RMS-values of time-domain vibrations, leaf spring truck
Figure 3d: CDF Kurtosis-values of time-domain vibrations, leaf spring truck

Figure 3a

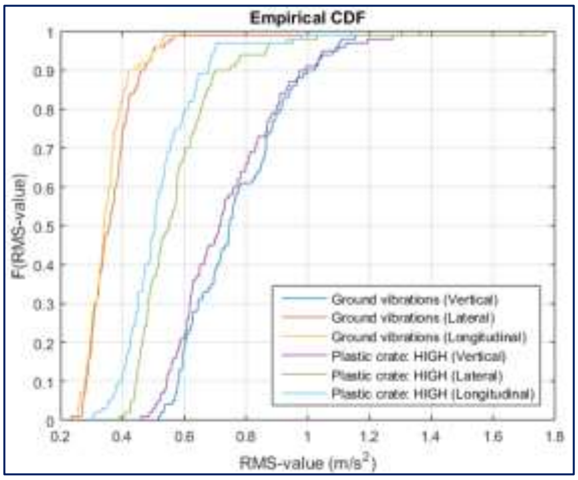


Figure 3b

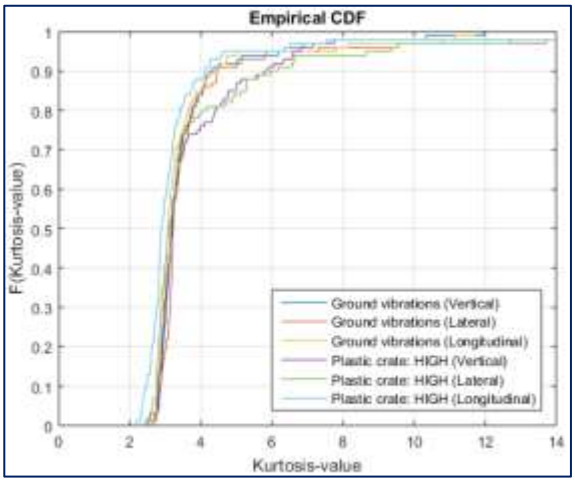


Figure 3c

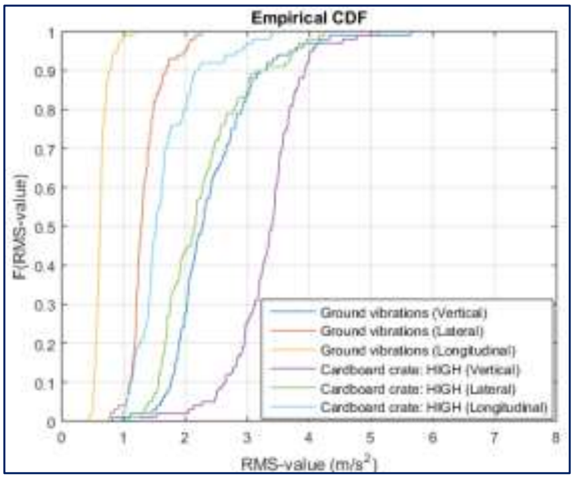
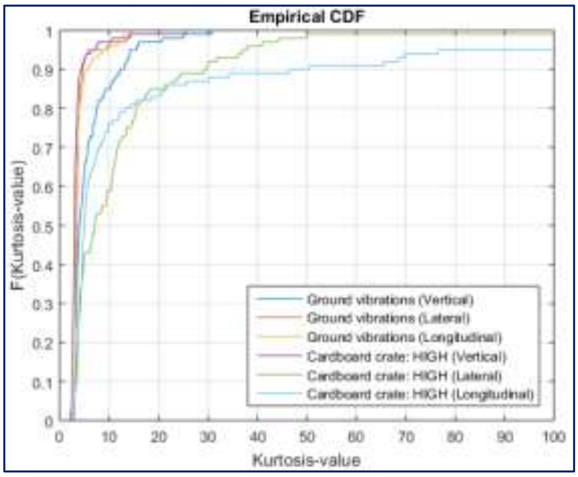


Figure 3d



Source: Own measurements

Stacking cardboard boxes or plastic crates on top each other results in higher RMS-values of the measured acceleration signals (in time-domain), as indicated in Figure 3a and 3c. This finding was also identified in literature (O'Brien, Gentry, & Gibson, 1965; Soleimani & Ahmadi, 2014). There are two effects causing this relation: with stacking boxes or crates on top of each other, the moment (of force) relative to the origin is larger. Additionally, the characteristics of the specific structure come into play (e.g. material properties and shape of the structure). The stiffness components and the damping parameters of the complete structure contribute to vibrations being amplified or attenuated. In order to further analyze the phenomenon, transmissibility curves (g^2/g^2) were calculated (Figures 4a and b). The authors of the study focused on the most relevant vibrations regarding frequency and acceleration with respect to future vibration simulation tests and (possible) beer quality degradation. Furthermore, the PSD plots (Figures 2a and b) confirm that noise was measured at vibrations higher than 150 Hz, and, therefore, were excluded for further analysis. As a consequence, the analyzed range of frequencies of the transmissibility functions of corrugated boxes and plastic crates are studied up to 150 Hz. While displacements at 125–150 Hz are small, the impact of high-frequency vibrations on beer quality are believed to be substantial.

Figures 4a and b indicate that the particular shape of the transmissibility curve is substantially different between bottles stacked in plastic crates versus cardboard crates. In both figures, vibrations between 1 and 25 Hz are amplified. Vibrations on bottles packaged in plastic crates will also amplify vibrations when frequency rises. The bottles in the highest crates are subject to vibrations between 75 and 150 Hz with up to nine times the amplitude of the pallet vibrations. The authors of the study attribute the measured results to both the configuration (bottles can freely move in the crate), as well as the (damping) characteristics of the crate. Additionally, the bottles move freely and generate vibrations that are picked up by other bottles (Paternoster et al., 2017). Bottles in cardboard crates, on the contrary, will attenuate vibrations higher than 100 Hz. The previously discussed phenomenon is more substantial with increasing the stack height of the cardboard crates. The highest crates attenuate vibrations higher than 50 Hz, although vibrations between 10 and 20 Hz are amplified by a factor of five to seven relative to the amplitude of the pallet vibrations. Results might be clarified by the specific beer packaging. In the plastic crates, beer bottles have free space to move and, as a consequence, are susceptible to increased high-frequency vibrations (75-150 Hz). In cardboard crates, bottles are separated with cardboard panels, which avoids bottles bumping into each other and absorbs vibrations. From the findings of this research can be concluded that food and beverage products packaged in cardboard boxes are subjected and vulnerable to transport vibrations lower than 25 Hz. Researchers often attempt to quantify postharvest losses due to simulated vibrations in a lab scale environment. Moreover, the researcher frequently limits the vibration experiment to imposing vibrations of a single frequency and acceleration. When using cardboard as a packaging material, which is frequently used as a packaging or cushioning material, we suggest focusing solely on vibrations smaller than 25 Hz when performing simulation tests.

Figure 4a: Transmissibility curve, plastic crates stacked on top of each other (Vertical direction)
Figure 4b: Transmissibility curve, corrugated boxes stacked on top of each other (Vertical direction)

Figure 4a

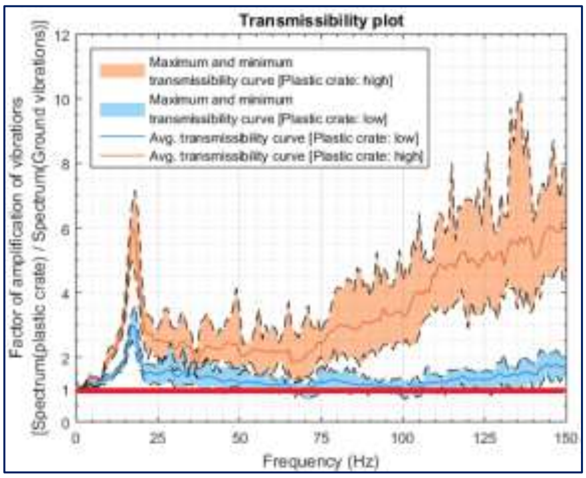
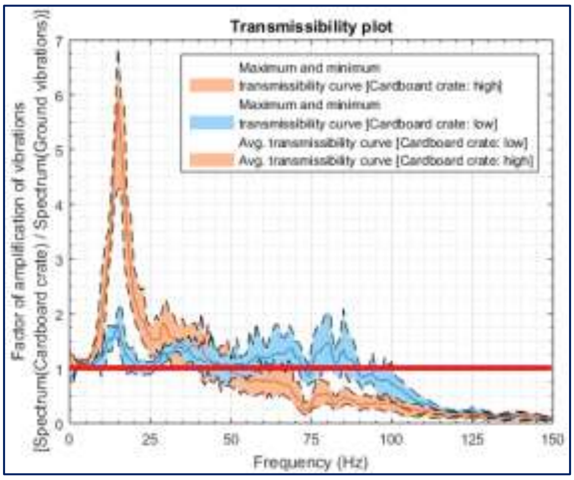


Figure 4b



Source: Own measurements

3.3 SHOCKS AND BEER PACKAGING

During truck transport, cargo is frequently exposed to shocks. The shocks that are measured mainly come from potholes and road unevenness (e.g. concatenation of two roads with different pavement structures). It is the purpose of product packaging to protect the product from shocks and, therefore, product damage. With respect to beer packaging, analysis was performed on the number of vibration samples (in time-domain) that were measured higher than 5 m/s^2 (peak) on the pallet floor (Figure 5a), on the beer bottle in a cardboard crate (Figure 5b) and in a plastic crate (Figure 5c). Only the histograms of measured signals (> 5m/s^2) of the highest stacked crates are presented since the corresponding histograms of peaks of the lower crates were of comparable order of magnitude. As indicated by the figures, the confidence intervals are not centered around the mean value. The latter can be attributed to the skewness of the distribution within every acceleration bin (e.g. 5-7 m/s^2). Furthermore, the results illustrate that when beer is packaged in plastic crates the counts of the measured acceleration samples (> 5m/s^2) expands in number, while the cardboard crate completely absorbs all shocks and, as a consequence, diminishes the number of shocks beer is exposed to. As a result, the performance of the cardboard crate in protecting the beer bottles from (response) shocks is significantly better than when using plastic crates [Appendix (3)].

Furthermore, individual shocks measured on the pallet, and beer bottles in the highest corrugated box and plastic crate were compared. With respect to the shocks that were measured on the pallet, the frequency of the damped oscillation (ω_d) is on average 333 ± 475 Hz. The damping ratio (β) of the analyzed shocks is on average equal to the dimensionless number 0.085 ± 0.024. With respect to the shocks on bottles of the corrugated box, ω_d is on average 115 ± 60 Hz, while ω_d of shocks on bottles in plastic crates is on average 321 ± 287 Hz. The damping ratio of shocks on beer bottles in corrugated boxes equals 0.076 ± 0.023, while in plastic crates is identified at 0.082 ± 0.031. Due to the intrinsic complex nature and the large variety of shocks during transport, the calculated damped oscillation and the damping ratio are large in standard deviation. However, current analysis validates the former results of Section 3.2 and 3.3. Moreover, the impacts bottles in corrugated boxes are exposed to are damped and, therefore, the frequency of the damped oscillation is lower compared to shocks on the pallet or on bottles in plastic crates. In plastic crates, bottles have free space to move and, as a consequence, shock-impacts generate high-frequency vibrations (also indicated by the transmissibility plot – Figure 4a). In a simulation environment, shock experiments can be modeled by approximating the frequency of the damped oscillation and the damping ratio.

Figure 5a: Histogram of time-domain vibrations (> 5m/s^2), pallet measurements (Vertical vibrations)
Figure 5b: Histogram of time-domain vibrations (> 5m/s^2), (high) corrugated box measurements (Vertical vibrations)
Figure 5c: Histogram of time-domain vibrations (> 5m/s^2), (high) plastic crate measurements (Vertical vibrations)

Figure 5a

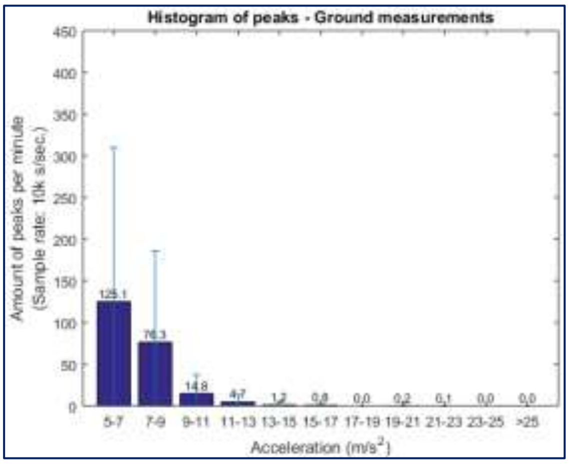


Figure 5b

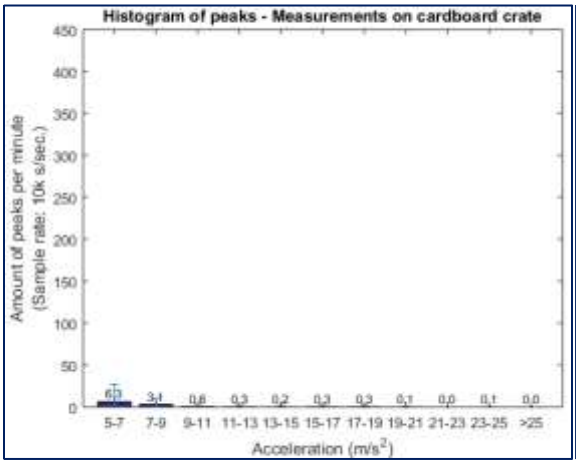
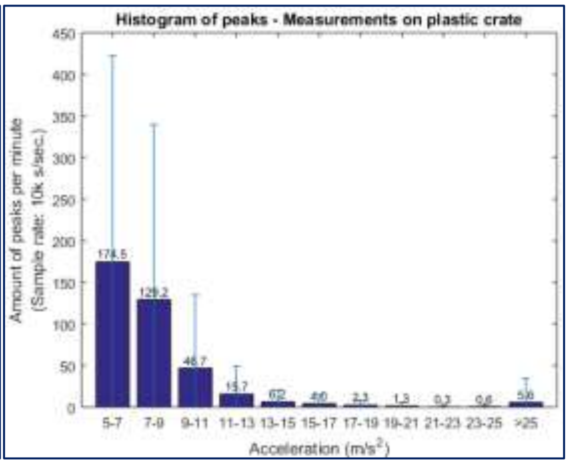


Figure 5c



Source: Own measurements

3.4 CASE-STUDY: VIBRATIONS, SHOCKS AND THE BEER FLAVOR QUALITY

Two explorative experiments were executed to identify the impact of vibrations and shocks on the beer flavor quality. In order to simulate transient vibrations, a drop device was manufactured that is able to mechanically and repetitively lift and drop a plastic beer crate (Figure 6a). More specifically, by controlling a motor that pulls a rod up and down that is fixed to an electromagnet, a small metal plate anchored to the plastic crate will induce the system to go up and to drop the crate[i]. A laptop with Matlab 2015a was connected to a data acquisition board

[i] Linear actuator: Nanotec, DC Linear actuator, L5918L3008-T10X2-A50
Controller: Nanotec, SMCI35 - Stepper Motor Driver, Positioning Control, 6 A, 24 Vdc to 48 Vdc
Elektromagnet: Stephenson Gobin, 58-0250 24 VDC - Electromagnet, Type 58, 24VDC, 5.4W, 750N, IP51

(National Instruments USB-6361) to control the device. A large pneumatic shaker of the company Bosal[II] (type MTS 258.05, max. amplitude 50 mm, max. force 50 kN) was used for the vibration experiment (Figure 6b).

Figure 6a: Experimental setup shocks and beer flavor quality
Figure 6b: Experimental setup vibrations and beer flavor quality (Vertical vibrations)

Figure 6a

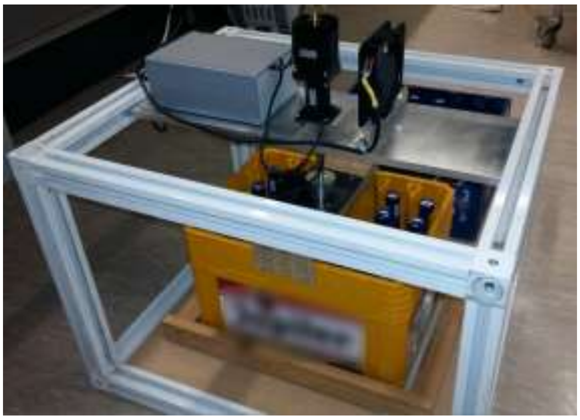


Figure 6b

Source: Own content

In the shock experiment, beer bottles (25cl. - Vichy) of a selected lager beer were subjected to 8100 shocks (3 days, 10 cycles of 270 shocks) with a drop height of 4 mm and an acceleration peak of 34.69 ± 4.75 m/s^2 (on bottle) in room temperature of 20°C. The frequency of the damped oscillation and the damping ratio was fixed to 153.74 ± 34.05 Hz and 0.19 ± 0.05. In the vibration experiment, beer samples (33cl. - Vichy) of four beer types (lager beer, blond specialty beer with and without refermentation after bottling, and dark specialty beer with refermentation after bottling) were exposed to vibrations of 15m/s^2 (0-peak) and 5, 15, 30 and 50 Hz during 4 days in room temperature of 20°C. The beer profiling parameters in this experiment are the oxygen concentrations (HSO –headspace oxygen–, DO –dissolved oxygen–), beer color, iso-α-acids, and aldehydes. Specifications of the performed chemical tests are described in Appendix (4).

With respect to the shock experiment, oxygen levels decreased slightly, i.e. HSO of 246 ± 29 ppb (ref.) – 188 ± 24 ppb (shocks) and DO of 26 ± 7 ppb (ref.) – 26 ± 4 ppb (shocks). Oxidative reactions are considered the initiator of the flavor aging reactions (Vanderhaegen, Neven, Verachtert, & Derdelinckx, 2006). However, no statistically significant findings were observed for the other parameters. With respect to the vibration experiment, both HSO and DO concentrations of all beer samples decrease due to all exposed vibration patterns (DO-measurements of the dark beer presented in Figure 7a). This indicates that an uptake of oxygen in the beer and the resulting beer flavor quality degradation might be present. However, no statistically significant findings related to the chemical parameters were observed for the vibrated beer samples except for the dark beer with refermentation after bottling (DSWith). The DSWith-samples had a high initial oxygen content (HSO: 658 ± 235 ppb, DO: 41.5 ± 18.8 ppb) and the aldehydes indicated to be sensitive to the vibrations. The concentration of the individual

Spindel: Nanotec, ZST5-5-200-1 - Threaded Screw Spindle, Linear ActuatorsT5x5, 200 mm

[II] Bosal subsidiary: Dellestraat 20, 3560 Lummen [Belgium] and total aldehydes of the DSWith-beer samples increased with rising frequency (Figure 7b, individual aldehydes in 'Data in brief'). Moreover, the Pearson R and Spearman ρ correlations indicate correlations larger than 0.729 for 8 out of 9 aldehyde components (12 data samples available) and, as a consequence, the hypothesis of having a monotonically increasing aldehyde concentration as a function of the vibration frequency is accepted on a significance level of 10%.

From the prior analysis can be derived that high frequency vibrations (30 Hz, 50 Hz) induce a more severe impact on the beer flavor stability than low-frequency vibrations (5 Hz, 15 Hz). Therefore, the highest stacked crates are more sensitive to transport vibrations compared to the lowest stacked crates (peak around 10-25 Hz in the transmissibility function – Figure 4a and b). Also, corrugated boxes perform better than plastic crates in protecting beer from vibrations since the high-frequency vibrations (> 25 Hz) are attenuated. Nevertheless, there is an uptake of oxygen at all vibration frequencies and, presumably, a high dependency on the initial oxygen content in the beer. Additional research is recommended on the interaction of vibrations with temperature and the possibility of delayed aging reactions due to the uptake of oxygen. Also, further research is suggested on the interaction between vibrations and shocks on the beer flavor quality.

Figure 7a: Measured DO concentration (relative scale) of DSWith-beer (dark specialty beer with refermentation) after the vibration treatment
Figure 7b: Measured total aldehyde concentrations of DSWith-samples after the vibration treatment

Figure 7a

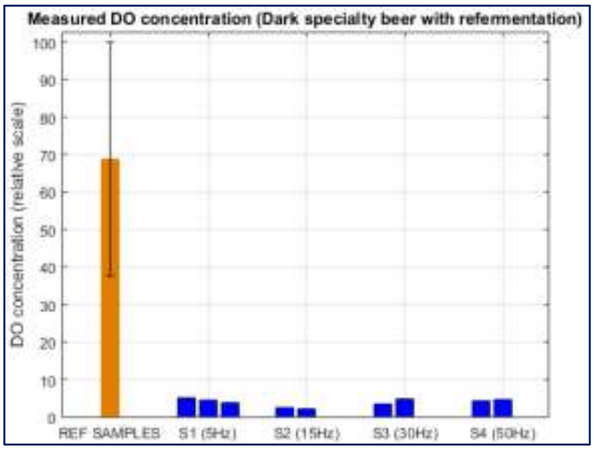
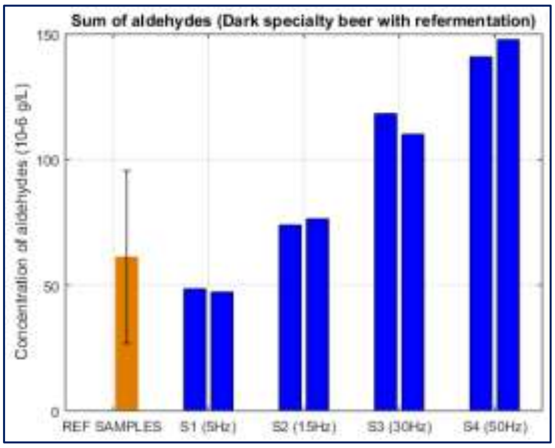


Figure 7b



Source: Own measurements

4. Conclusions and recommendations

From the results of the current paper, the following conclusions are derived:

- Power spectral density plots indicate the important prevalence of vibrations between 0.1 and 10 Hz. Spectral density results of vibrations measured on the Belgian road infrastructure are similar to the results described in literature between 0.1 and 10 Hz, and higher between 10 and 100 Hz (but comparable to ASTM D4169-16 DC3).
- With increasing the stack height of plastic crates or corrugated boxes, RMS-values of the vibrations in time-domain are elevated. Furthermore, the transmissibility curve of plastic crates identifies an amplification over the complete frequency domain with a peak around 5-25 Hz (of maximum a factor seven) and an increase with rising frequency. Vibrations between 75 and 150 Hz are increased up to a factor nine due to the stacking of plastic crates. The transmissibility curve of corrugated boxes identifies an amplification (of maximum a factor seven) between 5 Hz and 25 Hz and attenuation of higher frequencies with increasing stack height. When using cardboard as a packaging or cushioning material, vibration simulation tests should, therefore, focus on vibrations smaller than 25 Hz. Corrugated boxes perform better in attenuating vibrations and protecting beer from vibrations and, as a consequence, are preferred over plastic crates.
- Furthermore, when packaging products, the transporters should take into consideration that shocks of high amplitude are frequently present in transport over Belgian roads. Hence, products that are more sensitive to shocks than vibrations should be cushioned appropriately. Corrugated boxes absorb shocks and, therefore, protect beer bottles. A packaging with cardboard is preferred over plastic crates with respect to shocks.
- A first vibration and shock experiment identified the uptake of oxygen in beer due to vibrations and shocks, the dependency of the initial oxygen content, and the higher effect of high-frequency vibrations over low-frequency vibrations on the aldehydes. Beer in the highest stacked crates and beer in plastic crates are more sensitive beer flavor degradation due to vibrations and shocks compared to beer in the lowest stacked crates and corrugated boxes.

In future research, the effect of vibrations and shocks (in interaction with temperature) on the beer flavor stability of different beer types will be further investigated. This will result in a better assessment of the performance of the beer packaging in protecting beer from vibrations and shocks, and the need for the development of an adapted beer packaging.

5. Appendix

(1) Specifications of bottles, crates and plastic foil:
24 bottles of 25cl in a corrugated box with bottles separated with cardboard panels – Specifications bottle: Vichy (brown) – mass bottle: 494 g – mass crate: 11.86 kg (L x B x H: 36.5 x 24.5 x 24 cm)
24 bottles of 25cl in a hard plastic Polyethylene (PE) crate – bottle type: Vichy (brown) – mass bottle: 494 g – mass crate: 16.96 kg (L x B x H: 39 x 29 x 25 cm)
Transparent plastic polyethylene stretch foil (450 mm)

Beer 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 [empty beer bottles] 15 tons) – extra trailer 2 axles [Renders RMAC 9.9N] (length trailer 7.5 meters – weight full capacity 18 tons – end of transport [empty beer bottles] 13.5 tons) // Beer 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 [empty beer bottles] 15 tons) // Beer 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 [empty beer bottles] 16 tons) // Beer 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 [empty beer bottles] 16 tons)

(2) The pallet that was used for current experimental study was loaded on the last part of the extra trailer (beer transport 1), trailer (beer transport 2), trailer (beer transport 3) and trailer (beer transport 4) in order to measure the most extreme vibrations. Moreover, the pallet with the measuring devices was located 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]). All pallets had 7 layers of plastic crates that are 'clicked' on top of each other. The 'clicking' is possible due to the structure of the plastic crates and ensures safe stacking of crates. All studied pallets have 5 layers of corrugated boxes in which bottles are separated from each other with cardboard panels, which is the industry standard. The corrugated boxes were then stabilized with stretch-wrap.

The authors of current paper indicate that close to all food products are transported in their (secondary) packaging and stacked on pallets. Also beer is stacked on wooden pallets in order to facilitate loading and unloading of beer. 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.

All bottles were the same for the studied beer transports and contained 33 cl of beer. The bottles with the accelerometers mounted on them stay in the same orientation since the cable hinders them to change direction and balances the bottle. However, the bottles have enough free space to move in order to not affect the normal operation or movement of the bottle.

(3) It is difficult to extract the input versus the responses of the shocks. However, the authors of current research are predominantly interested in the shock response phenomena to identify the conditions bottled beer is subjected to. Post analysis revealed that the frequency of the damped oscillation is predominantly higher than 100 Hz for both shock responses measured on the pallet and the bottles in the plastic crates. Therefore, even with an amplification of the vibrations lower than 50 Hz by a factor seven for the bottles in the highest stacked corrugated boxes , bottled beer in both high and low corrugated boxes will not be exposed to many shocks. The latter can be attributed to the structure of the material (corrugated cardboard) and the cardboard panels between the bottles that absorb the energy of the generated (response) shocks.

(4) Specification of the performed chemical tests:

- Oxygen:
  Determination of oxygen concentrations:
  Oxygen in bottled beer is determined using the 'Haffmans Inpack TPO/CO_2 meter Type c-TPO'. The measurement is performed in a sealed bottle and the principle is based on O_2 dependent fluorescence of the sensor.
- Beer colour: IOB method: 9.1 (The Institute of Brewing, 1997);
- Iso-α-acids:
  UPLC determination of iso-α-acids:
  UPLC separations were performed on an Acquity UPLC (Waters, Milford, USA), consisting of a PDA detector, column heater, sample manager, binary solvent delivery system and an Acquity UPLC HSS C18 1.8µm column (2.1 i.d. × 150 mm; Waters, USA). Data reprocessing: Empower 2 software. Chromatographic conditions: eluent A: milli-Q water adjusted to pH 2.80 with H_3PO_4 (85%, Merck, Darmstadt, Germany); eluent B: HPLC-grade CH_3CN (Novasol, Belgium). Elution: isocratic using 52% (v/v) solvent B and 48% (v/v) solvent A. Analysis time: 12 min. Flow rate: 0.5 $mL.min^{-1}$. Column temperature: 35°C. UV detection: 270 nm.
- Aldehydes:
  C-MS determination of aldehydes:
  Volatile aldehydes in beer were determined according to (Vesely, Lusk, Basarova, Seabrooks, & Ryder, 2003), using headspace-solid phase microextraction (HS-SPME) with on-fibre PFBOA (*o*-(2,3,4,5,6-pentafluorobenzyl)hydroxylamine) derivatization and capillary gas chromatography/mass spectrometry (CGC/MS) (Dual Stage Quadrupole (DSQ™ II) GC/MS system, Interscience Benelux). The DSQ™ II was coupled to a Thermo Trace GC Ultra (Interscience Benelux) equipped with a CTC-PAL autosampler (including SPME sampling), a split/splitless injector with a narrow glass inlet liner (0.5 ml volume), and a RTX-1 fused-silica capillary column (40 m × 0.18 mm i.d. × 0.2 µm film thickness, Restek, Interscience Benelux). Data reprocessing was done by the XCalibur™ data system (Thermo Electron Corporation).

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