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Measuring the Mechanical Effects of Egg Transport in Field and Modelled Conditions

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Global food demand is expected to double by 2050, putting immense pressure on agro-food supply chains. As non-agricultural activities gain prominence within the food supply chain, a systemic approach is needed to address sustainability challenges. However, this is a learning process, because of the complexity of hatching egg transport, similar to a three-arm balance of transport condition, packaging material and egg quality. Changes made in the name of sustainability can sometimes cause unintended negative effects.

Plastic trays are often favoured over paper ones for sustainability purposes in egg transport. However, they may contribute to higher egg breakage and reduced hatchability, increasing the carbon footprint due to the loss of day-old chicks. Since hatching eggs are more valuable than table eggs, any damage during transport results in greater economic loss.

This study investigated the mechanical impact on eggs during 41 road transports, utilizing g-force acceleration loggers to collect data. A significant relationship was found between cargo weight, egg breakage, hatchability, embryo mortality, and g-force frequency. Seasonality also played a crucial role in hatchability, even when transport temperatures were within acceptable limits.

Simulated trials using vibrating transport devices were conducted to better control mechanical impact. Eggs from one flock were used to minimize variables. Results showed a significant ($P<0.05$) reduction in hatchability (91.06 % vs. 82.81 %) when transported on plastic trays compared to paper ones. At higher vibration levels, even paper trays could not protect the eggs, with hatchability decreasing significantly ($P<0.05$) to 64.8 %.

These trials indicated that plastic trays had a greater negative impact on hatchability, but at extreme impact levels (47.22 m/s^2), even paper trays failed to offer adequate protection, reducing hatchability by 15.9 %. Considering both hatchability losses and egg breakage provides a more comprehensive understanding of sustainability in egg transport, raising the question of whether plastic trays are truly sustainable if transport conditions cannot be improved.

1. Introduction

As Carter (1970) stated, "An egg shell cracks if the strength of the shell is less than the strength of the environmental insult to which it is exposed”. All egg handling and transport methods should be evaluated based on this principle. Packaging materials play a crucial role, either mitigating or exacerbating the impact on eggs. To fully understand mechanical effects during transport, more detailed data on transport conditions, packaging, and egg characteristics is necessary.

Despite of the importance and the damage can be caused by the transport condition, the available literature is limited and no comparison was made on plastic and paper trays and their different impact on hatchability.

The damaging effects of egg transport have been long recognized. Nethercote et al. (1974) identified key factors such as vehicle suspension, road traffic, cargo placement, driving style, and atmospheric conditions. In his work he is examined different paper and expanded polystyrene. While Berardinelli et al. (2003) examined carboard packaging, and further highlighted road quality, speed, distance, and truck characteristics as important variables affecting egg transport. Subject of both works were table eggs. Randal et al. (1993) study on poultry transport highlighting the number of shocks during transport also plays a significant role in cargo integrity.

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Research by Sun and Nguyen (2023) revealed that the distribution of load across axles significantly affects dynamic tyre force, whereas the total vehicle weight has a minimal impact. Additionally, Fan et al. (2018) demonstrated that emissions per 1 t of goods rise if the vehicle is not fully loaded. Thus, from a sustainability perspective, fully loaded deliveries are more efficient, though heavy trucks should be designed to distribute dynamic loads evenly (Sun and Nguyen, 2023). However, emissions due to transport only one side of the three-armed balance. If products are lost during transport, the carbon print of the unit of product will increase.

The impact of transport and vibration on both the external and internal quality traits of eggs is crucial, as these factors significantly affect hatchability. While shell breakage is the most evident form of loss, it is largely determined by eggshell strength (Carter, 1970). Nazareno et al. (2013) observed that eggs from older or middle-aged flocks, which have thinner shells, had higher breakage rates (2.1 %). Additionally, Altuntas et al. (2008) found that larger eggs require less impact to break.

Mertens et al. (2006) demonstrated significant differences in eggshell strength (including shell stiffness and damping ratio) among eggs from chickens housed in different systems, whereas Zsedely et al. (2024) reported no effect of rearing systems on shell strength, albumen height, or Haugh units.

Regarding internal changes, Mertens et al. (2006) noted that excessive vibration affects not only the eggshell but also the internal quality of the egg, as vibrations increase the likelihood of cracks and breakages, disrupting the egg's internal structure. In this trial, table eggs and paper packaging were used, similar to Berardinelli et al. (2003), who studied how vibrations impact albumen quality (Haugh unit) and vitelline membrane strength. Their findings showed that vibration levels varied depending on cargo placement and transport speed, with higher levels recorded at the rear and top of vehicles.

The literature regarding the mechanical impact on hatchability is very limited. Donofre et al. (2017) reported that high vibration levels and longer exposure negatively affected hatching results and mid-term embryonic survival, while low-level vibration impacted late embryo deaths. In their work, plastic trays were used, and HOBO loggers with a measuring limit of 29,4 m/s^2. Copur Akpinar and Günec (2019) showed a similar decrease in quail eggs, where hatchability showed a correlation with the storage duration x transport distance interaction. In this work, there is no information on logger data or tray type. Tullett (2009) also noted that rough handling and shaking during collection and transport can lead to deformities and developmental abnormalities, but no threshold was stated in his work.

Transporting hatching eggs on reusable plastic trays has become more popular due to sustainability concerns, but understanding the potential damage to hatching eggs and its effects on hatchability remains critical.

Despite the availability of piezo sensors and data loggers for monitoring mechanical impacts, the use of these technologies in daily practice is still uncommon. However, it has a negative effect on hatchability. Besides, either no -g-force loggers were used, or the impact might exceed the measuring limit of the logger.

This study examined the relationship between filed transport conditions, egg breakage, and hatchability losses across different flock ages and storage durations.

Based on the field measurements, trials were conducted to simulate transport conditions using vibrating machines, assessing the effects of plastic and paper trays and and comparing increased vibrations on paper trays to determine a threshold when hatchability decreases also on the gentlest packaging. The findings underscore the importance of constant monitoring of transport conditions and evaluating hatchability decline alongside breakage losses.

2. Materials and methods

Following field observations, a vibrating plate was used to simulate transport conditions and minimise influencing variables. The vibrating machine was selected based on initial transport measurements to ensure consistent and controllable mechanical impacts.

Tinytag® TGP-0605 high-sensitivity shock loggers were employed to monitor and record mechanical impacts, measuring acceleration in g-force (approx. 9.8 m/s^2), with a measuring range of 0-49 m/s^2.

Data were analysed by distribution across different ranges, frequency of extreme measurements, and average and root mean square (RMS) values. During field observations, loggers were placed atop egg pallets, typically at the back of the cargo. Data were collected year-round over 41 road transports, lasting between 55 and 101 h depending on route, season, and regulatory rest breaks (as per EC No 561/2006). All trucks were equipped with air suspension and climate control, with loads ranging from 11 to 25 pallets.

During trials, Tinytag® TGP-0605 loggers were attached to the vibrating plate, which moved in two dimensions. The machine allowed for steady 20 or 30 Hz vibrations or periodic changes between 10-30 Hz. Each trial used a 10 min impact time.

Trial 1 involved eggs on paper trays vibrating at either 20 or 30 Hz.

Trial 2 tested periodic vibrations between 10-30 Hz, with one group using paper trays and another using plastic trays, since plastic trays are commonly used to reduce packaging material waste, promoting sustainability.

Field data covered a variety of flock origins and ages (27-64 weeks). Upon delivery, records were kept of the pallet's location and number of broken or hairline-cracked eggs, and eggs were tracked by the flock, recording embryonic mortality, hatchability of fertile eggs, and chick quality. Early embryonic mortality was assessed through candling on the 10th day of incubation, followed by egg break-out analysis. Storage time before incubation was also noted due to its influence on hatchability and chick quality.

During trials, eggs from a single young flock were handled consistently before and after vibration treatments to control for environmental, age, and nutritional differences. Eggs were incubated in the same incubator with randomised distribution. Each trial included three sets of nine trays, with each tray holding 150 eggs, serving as an individual observation unit. Unhatched eggs were analysed following Tullett's (2009) method to assess embryonic death stages, deformities, malpositions, and hatchability of fertile eggs.

Statistical analyses were conducted using IBM SPSS Statistics, including Pearson correlation, ANOVA, and stepwise regression models.

3. Results and discussion

Field transport data showed a significant ($P<0.05$) effect of cargo weight on g-force data and distribution in different measurement ranges. Driving time significantly ($P<0.05$) affected calculated mean and g-force below 30 m/s^2 but did not impact hatching parameters. Season significantly affected the frequency of maximum g-force measurements ($P<0.05$) and all hatching parameters ($P<0.01$).

The logger position was vertical at the cargo's end, fixed on top of the pallet, as Nazareno et al. (2013) observed that the worst vibration and shock loads occurred in the vertical direction (front to back), causing more breakage on asphalt roads.

In two cases, front and rear locations were monitored during the same delivery (Figure 1.).

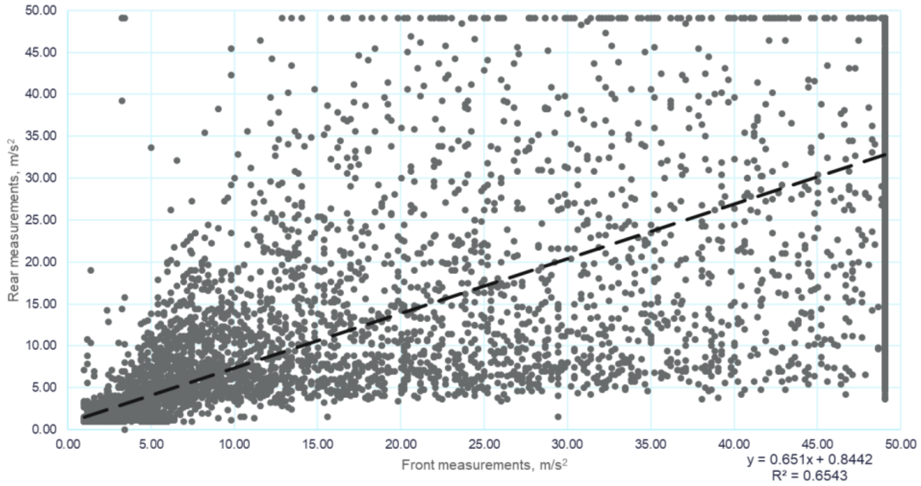

Figure 1: Front vs rear measurements on the truck (Pallett No1. and No23.)

Field observations indicated that rear pallets mostly experienced higher mechanical impacts. This aligns with Berardinelli et al. (2003), who measured higher values at the vehicle's rear and top column boxes. However, their sensors were directly installed on the eggs, possibly explaining the difference. Average and RMS (root mean square) values were higher at the front (13.6 m/s^2 and 22.6 m/s^2) compared to the rear (9.37 m/s^2 and 17.17 m/s^2). The difference can be explained by the frequency of values measured in the 41-50 m/s^2 range, suggesting spectral density analysis of long-delivery data can be informative and support the idea of a loading plan and select the best place to load eggs with more fragile eggshells, would decrease the loss due to egg breakage. As shown in Figure 1, the data accumulation at the maximum also suggests that the values reached the measuring threshold of the logger. Data calculated from the logger data of all observed deliveries are presented in Table 1.

Table 1: Logger results of 41 field deliveries

	Average, m/s^2	Root mean square, m/s^2	<10 m/s^2	11-20 m/s^2	21-30 m/s^2	31-40 m/s^2	41-50 m/s^2
Average	9.7	13.18	65.8	19.1	5.5	2.2	4.7
Maximum	29.9	34.9	92	43.1	12.3	7.7	43.6

Hatch of fertile eggs showed strong, negative correlations with season (r= -0.69) and early dead level (r=-0.69), moderate with broken/cracked eggs (r=-0.46), ($P<0.01$). Seasons were numbered from 1 to 4, where 4 is winter. When regression is calculated it revealed the biggest impact is the level of broken/cracked eggs and embryos died in the early stage of incubation. This underlines the impact of losing embryos, besides hatching eggs.

Hatch of fertile eggs, % = 107,04-8,2 x Broken/cracked % -3.32 x Early dead, % - 1,19 x Season. $R^2 = 65.9$.

Early dead level had a strong negative correlation with season (r=-0.60) and moderate, positive with length of storage (r=0.47) and with broken/cracked eggs (r=0.30), ($P<0.01$).

At spring, hatchability increased mostly due to the decrease in early death. Broken/cracked egg percentage showed a moderate (r=0.30) correlation with the early dead level and with the season (r=0.55), resulting in lower hatchability in winter ($P<0.01$).

Season showed moderate correlation with the frequency of g-force data in different ranges, positive with the highest range (r=0.335) and negative moderate with the lowest range (r=-0.343), ($P<0.01$), which indicates less frequent higher g-force values in summer compare to autumn.

A significant correlation between the field transport logger database and hatchability cannot be detected, but the cracked/broken eggs percentage showed a moderate, significant correlation between the number of pallets on the cargo (r=0.32) and the frequency of data in the highest range (r=0.37), ($P<0.01$). The duration of the delivery time showed a moderate positive correlation with the measured g-force above 30 m/s^2(r=0.55).

A modelling vibration machine was introduced in the trials to control variable factors during field transport, allowing for the assessment of the effect of mechanical impact. Field transport data RMS (root mean square) values ranged from 4.1-34.9 m/s^2, while experimental conditions were modelled between 23.68 and 47.72 m/s^2 on the vibrating plate machine (Table 2).

Table 2: Logger results for constant vibration on 20 or 30 Hz for 10 min (Trial 1) and periodically altering the vibration between 10-30 Hz (Trial 2)

	Average, m/s^2	Root mean square, m/s^2	<10 m/s^2	11-20 m/s^2	21-30 m/s^2	31-40 m/s^2	41-50 m/s^2
Trial 1. 20 Hz	23.0	23.68	2.3	15.2	74.8	7.1	0.6
Trial 1. 30 Hz	47.22	47.72	2.5	3.5	4.1	4.1	85.8
Trial 2. 10-30 Hz	36.9	37.2	23.5	7.6	6.6	11.2	51.1

Hatchability of fertile eggs significantly decreased compared to control groups when steady 30 Hz vibration was applied on paper trays, with a 3.9 % and 15.9 % drop (Trial 1, Table 3.).

When eggs received periodically altering vibrations between 10-30 Hz on plastic trays, an 8.2 % hatchability drop was observed (Trial 2, Table 4.). The decrease in hatchability was mainly due to increased early dead embryos. Eggs vibrated at 30 Hz on paper trays had 9.8 % more early dead embryos, while periodically altering vibrations on plastic trays caused a 3.9 % increase compared to control groups. Mechanical impact primarily worsens hatchability by increasing early dead embryo rates (Trial 1 and 2).

Higher early embryo death rates were expected based on field observations. Besch et al. (1965b) found that acceleration forces can cause blastoderm cell detachment, affecting hatchability.

In the 1st experiment, the significant difference observed in the proportion of middle-aged death embryos (0.56 a±0.70 vs. 1.68 c±0.88) between the group shaken at 30 Hz and the control group was unexpected since, in this stage of life, the embryos are more resistant and the proportion of embryonic deaths the lowest. The results align with the findings of Donofre et al. (2017), whereas the odds of an embryo dying in the intermediate period (6 to 17 days) were significantly different between the maximum vibration, maximum exposure time, and the control. The highest deformity rates were detected with steady 30 Hz vibration for 10 min on paper trays, including facial deformities, duplicated spines, or limb multiplication.

Since the rate of early dead embryos was significantly lower for eggs treated on paper trays, the hatchability per fertile egg was still 4.1 % higher than for eggs shaken on plastic trays (Trial 2)

An explanation for this can already be found in Dareste's works written in 1891, which described that if the eggs are left to stand for 2 days after transport, the embryo development is normal, while it is abnormal in eggs incubated immediately after transport. De Lange (2012) suggests that the eggs should be rested for at least 12 h after delivery before hatching; otherwise, the proportion of early dead embryos may increase.

For both experiments, the incubation started 24 h after vibration.

Landauer and Baumann (1943) noted fewer abnormal embryos when eggs rested 48 h post-transport before hatching. Longer mechanical exposure increased abnormal embryos, influenced by pre-impact storage duration and season, affecting the germ disc's condition. However, deformities are not the main cause of the drop in hatchability, but they can be considered as a warning sign of the negative effect of mechanical impact.

On the one hand, deformities can be said to be indicative, so their appearance as a symptom must be monitored. On a few embryos, the deformity was visible with bare eyes as early as Hamburger Hamilton stage H17-20. (Hamburger and Hamilton, 1992). During field observation, deformities were noted that were not yet visible to the naked eye and died in the membranous (died at 24-28 h after launching incubation) or blood ring stage, causing distortion and the embryo did not develop further. A magnifying glass was used to document these cases. The results resemble Dareste (1891) drawing about abnormal embryos. In the trials the increase of late dead embryos was not significant (P>0,05), although according to Donofre (2017), the mechanical effect significantly increases the proportion of late dead embryos.

However, increased level of malposition embryos (not correct hatch position) was detected in both trials.

Two main types of malposition were determine based on Tullett (2009). Malposition 2: Head in small end of egg and Malposition 6: Beak above right wing. In case of malposition 2 it can be attributed to the fact that the low-mass eggs turned over on the tray due to the shaking. as the embryo in an upside-down tray will also be upside down before hatching. Malposition 6 requires further investigation into how transport affects the condition of the shell membrane. Elibol and Brake (2002) supported this by stating that adequate turning helps counteract the negative effects of storage on shell membranes, facilitating normal development of the chorioallantoic membrane and facilitate normal oxygen supply. Insufficient oxygen supply can also impact the development of malposition.

During their work, Besch et al. (1965a) found that hatching loss was mainly due to damage caused by the force exerted on the shell. In the present experiments, most of the hatching loss cannot be attributed to this, as I did not find a significant correlation between the experimental and control groups. This probably also contributes to the fact that in the experiments I used eggs from young flocks, whose shells are known to be stronger or the control group value was also higher due to the egg handling issues on the farm.

Table 3: Trial 1. Hatchability and egg-break-out results in control and treated groups (constant vibration on 20 or 30 Hz for 10 min

	Hatch of fertile eggs, %	Early dead of fertile eggs, %	Mid dead of fertile eggs%	Late dead of fertile eggs%	Broken, cracked eggs%	Deformities, %	Malposition, %
Control	80.7^{a}±1.39	9.66^{a}±1.74	0.56^{a}±0.70	2.99 ^{a}±1.16	1.78^{a}±0.89	0.55^{a}±0.59	1.89^{a}±1.27
20 Hz	76.8^{b}±2.97	11.15^{a}±3.12	0.39 ^{a}±0.37	2.92 ^{a}±1.69	1.50^{a}±0.89	1.27^{ab}±1.06	3.37 ^{a}±1.84
30 Hz	64.8^{c}±4.27	19.52 ^{c}±4.76	1.68 ^{c}±0.88	4.69 ^{a}±2.44	1.50^{a}±0.88	1.85^{bc}±0.77	3.20 ^{a}±0.97

a,b,c Different letters indicate a significant difference at the P<0.05 level.

Table 4: Trial 2. Hatchability and egg-break-out results in control and treated groups (periodically altering the vibration between 10-30 Hz) on paper or on plastic trays for 10 min

	Hatch of fertile eggs, %	Early dead of fertile eggs, %	Mid dead of fertile eggs%	Late dead of fertile eggs%	Broken, cracked eggs %	Deformities, %	Malposition, %
Control	91.06^{a}±4.59	1.58 ^{a}±1.19	0.59 ^{a}±1.09	4.73 ^{a}±4.61	0.81 ^{a}±0.55	0.23 ^{a}±0.47	3.29 ^{a}±1.76
Paper tray	86.90^{ab}±4.44	2.86 ^{bc}±1.92	1.13 ^{a}±1.13	6.85^{a}±3.68	0.46 ^{a}±0.44	0.72 ^{ab}±0.68	3.92 ^{a}±2.05
Plastic tray	82.81^{b}±5.32	5.53 ^{ac}±2.73	2.15 ^{a}±2.66	6.34^{a}±5.01	0.88 ^{a}±0.74	0.11 ^{ac}±0.34	4.67 ^{a}±2.82

a,b,c Different letters indicate a significant difference at the P<0.05 level.

4. Conclusion

Field data indicates that egg quality, particularly related to factors linked to flock age, such as eggshell strength, plays a significant role in outcomes, while seasonal variations influence hatchability. Maximum truck loads led to higher g-force frequencies at the rear pallets, and limited observations suggest that the back of the truck faces greater impacts during acceleration and braking. By monitoring various positions on the truck and selecting optimal loading areas for eggs with fragile shells, breakage losses can be minimised.

Plastic trays, when subjected to the same vibration levels, caused a greater reduction in hatchability compared to paper trays. Assessing eggshell quality or monitoring breakage during transport is essential. If improving eggshell quality isn't feasible, or road conditions are particularly rough, switching from plastic to paper trays for certain age groups may help reduce losses. Broken eggs not only cause economic damage but also increase the carbon footprint. However, the study shows that even paper trays cannot fully protect eggs from the mechanical effects of vibrations at 20 Hz or higher, even for durations as short as 10 min.

Monitoring embryo deformities can also reveal signs of rough handling before incubation. This analysis can help determine whether plastic trays are a sustainable option or if corrective measures—such as improving transport vehicles, adjusting conditions, modifying packaging materials, or enhancing eggshell quality—are necessary.
Further research is required to understand the causes of malpositions, as these also negatively impact hatchability. Field data suggests testing different types of plastic trays with more elasticity and larger surface contact to reduce the forces transmitted to the eggs.
In our upcoming study, the focus will be on eggshell quality, and field monitoring will use mechanical loggers with a wider range for more accurate measurements.

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