Impact Shock Events in Multimodal Container Transshipment for Packaging Testing

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In modern global supply chains, intermodal and multimodal distribution has become essential means of transportation. The combination of different modes of transport is the most commonly used method for distributing shipments between continents. This paper examines and measures physical events, such as shock and impact, that occur while transporting 40ft long ISO containers using multiple modes of transport. These events can directly affect the integrity of packaged products and cause damage. The study focuses on events such as transshipments and handling of containers in hubs and terminals. The impact shock levels were separately analyzed in all three-dimensional directions, namely vertical, longitudinal, and lateral. The results indicate the percentage of occurrence below a given impact level using statistical characteristics of the events that occurred. The magnitude and mean of acceleration levels, pulse duration, and velocity change are also reported.

Keywords: *ISO container, packaging, shock, impact*

1. INTRODUCTION

Packaged products are transported worldwide using various modes of transportation, such as ground trucks, railcars, and overseas vessels. Multimodal transpor–tation involves using standardized containers of diffe–rent sizes to carry out these delivery tasks. These conta–iners can transport FCL (Full Container Load) or LCL (Less than Container Load) goods. Forwarders prefer the ISO container because it is easy to handle and tran–sfer between different modes of transportation. In 2021, the volume of containerized cargo trade reached 168.20 million TEU (twenty-foot equivalent) [1]. But the most generally used shipping container is the 40 ft long ISO standard container. This can be seen in Figure 1.

Figure 1. 40 ft long ISO container

This is why observing and analyzing physical events during distribution is important. This can provide engi–neers with comprehensive information to design suitable protection for goods during shipping. Containerized goods are often handled multiple times at terminals, hubs, and ports, which can lead to physical events that directly affect the integrity of the products inside. These events can be a primary source of shipment damage [2]. This paper observes and analyzes impact shock events during container handling at various ports and terminals in different continents and countries, including Hun–gary, Slovakia, Poland, the Czech Republic, Belarus, Russia, Germany, Mexico, South Africa, and India, as well as China. Figure 2 shows container transshipments at seaports and terminal railway hubs.

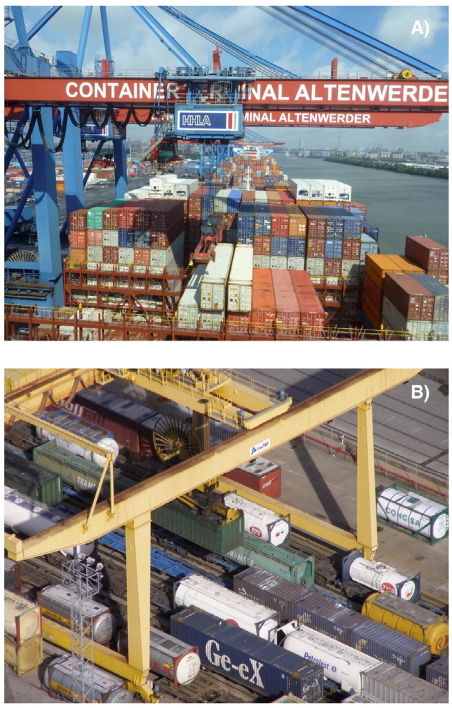

Figure 1. Container transhipments at a) seaport and b) rail–way terminal

During handling operations, containers are subject to shocks generated by impacts between containers, solid ground, or vehicle body structures. These shocks can cause freight damage [3,4]. Of course, these effects can

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happen at different levels. For instance, careful handling can reduce their occurrence or intensity; cushioning and space-filling material can be applied to limit the shock effect on the freight. The efficiency of these preventive methods highly depends on the identification and characterization of the shock levels.

Impact shock can be characterized by a sudden and severe motion produced when two bodies collide or when a moving object or surface strikes a stationary one. In container shipping, it refers to the sudden stop of a moving container upon impact with the ground, another container, or a transport vehicle.

In the packaging field, this mechanical shock could result from the physical movement of goods, mainly due to handling.

Only a few studies have been conducted on shock and acceleration impacts inside intermodal containers. Most have focused on measuring vibration levels during single-trailer truck trips and developing PSD profiles for random vibration conditions [5-12]. Only two studies observed shock events during truck transportation [13-14]. In the case of vibration analysis, power density (PD) levels are determined as a function of frequency based on recorded random vibration acceleration levels [15-18]. But shock and vibration events must be separately examined to conduct packaging laboratory simulations [19].

After examining the relevant literature, the authors found no published studies that have quantified and grouped shock and impact events during containerized transportation dedicated to investigating acceleration shock levels experienced during transshipment and handling events of intermodal containers. Given this knowledge gap, the present paper aims to provide new information on the actual physical impact of multimode transport on shipments. This study focuses only on the mechanical shock related to the physical movement of multimodal containers causing significant physical effects on freights and products inside.

Figure 3. SAVER™ 3X90 Shock Data Recorder

2. EXPERIMENTAL DESIGN

2.1 Measuring equipment

This study collected data from a Lansmont SAVER™ 3X90 field data recorder (Lansmont Corp., CA, USA) (Figure 3). The recorder measured all impact and shock events in all three orientations (vertical, lateral, and longitudinal).

For each measurement segment, the recorder was mounted directly to the floor and inside the container (Figure 4). This data recorder has a lithium-ion battery with an internal triaxial accelerometer that can provide power to record data for approximately 90 days.

The instrument records data to a simple flash memory if any signal exceeds a desired threshold limit. Data can also be triggered to record at user-selectable wake-up intervals. The anti-aliasing filter is based on a 4-pole, low-pass Butterworth filter. The recorder settings used for this study are shown below:

- Signal trigger: 0.5 G
- Recording Time: 2.048 s
- Sample/sec: 500 Hz
- Sample size: 1024
- Anti-aliasing filter frequency: 100 Hz
- Pre/post trigger: 20/50%
- Memory allocation: 6625 events
- Active channels: x, y, and z

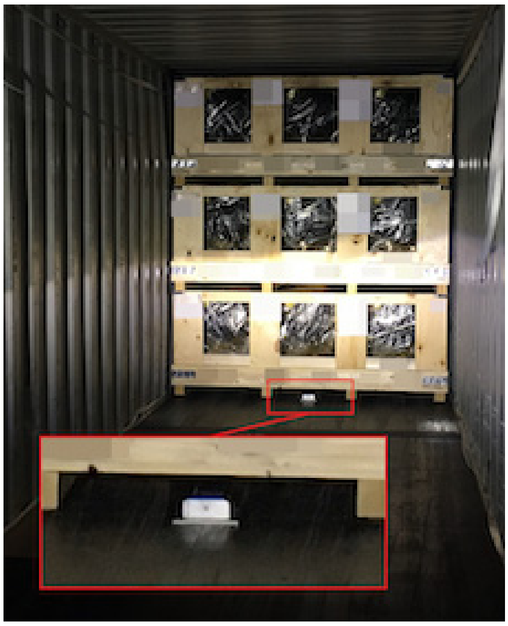


Figure 4. Position of data recorder in container

Generally, the trigger threshold parameter level using a field survey can cause confusion in interpreting impact shock events. The reason is that the survey's original goal influences this parameter. If the aim is to observe those severe shock levels that can affect the freight integrity or lead to damages, then this trigger level should be used with a relatively high value. Although many shock events may well go unrecorded in this way, combining the data without real meaning content to compute statistical characteristics is not recommended.

2.2 Delivery conditions of shipping

Five multimodal shipping measurements were observed for this study, conducted between 2017 and 2022. Table 1 contains some specifications for each shipping route.

Thirty-two transhipments and/or container handling events were recorded in nine countries. In each case, the shipping originated from Hungary (Europe) to five des–tinations worldwide, including three continents (Asia, Africa, and North America), using semi-trailer trucks, railcars, and cargo vessels for delivery. This can be seen in Figure 5.

Table 1. Delivery routes for shipping

Destination	Number of transshipments	Transshipment location
China	6	Tianjin, Changchun, Harbin
India	2	Mumbai, Aurangabad
Mexico	2	Veracruz, San Jose Chiapa
Slovakia	4	Dunajska Streda
Hungary	6	Győr
Belarus	1	Brest
Russia	1	Zabaykalsk
Germany	8	Hamburg, Bremerhaven, Bad Rodach, Reutlingen
R. of South-Africa	2	Port Elizabeth, Uitenhage

The load of every delivery task consisted of auto–motive parts for assembling plants. The total distance and duration of all transportation observed in this study were 3 127 km on truck trailers, 13 227 km on inter–modal railcars, and 109 days on container ships. The payloads were between 16 160 - 22 695 kg.

Figure 5. Locations of transhipments for this study

2.3 Shock detection

In intermodal containers, shocks often appear as high amplitude and short-duration acceleration events. A shock impulse is usually determined as a non-periodic event and implies a degree of suddenness and severity [20]. For this study, shock impulse was if the following two conditions were done:

- The event value is greater than 0.5G.
- The event value is over three to four times the RMS level of the given recorded signal.

If both conditions are satisfied, the event amplitude is stored in the flash memory with its pulse duration.

The shock duration usually depends on the amount of cushioning for the mechanical system, but this does not apply to steel containers. So, any surface or part of the container that meets another container or ground floor, or vehicle body can be a source of a rigid impact of the two mechanical systems.

Figure 6 shows a typical impact shock waveform resulting from an impact with those components of a shock impulse that can be characterized. The first observation is the peak acceleration (or G level) observed during the event. At this step, the maximum faired acceleration must also be determined using the filter method to clarify the impulse signature. The second determination is the pulse duration over the event that occurred. Shock pulse is usually measured in a range of 2 to 50 ms [22]. As the last step, the velocity change that occurs can be derived. This velocity change is proportional to the area under the acceleration time history curve; it is the integral of acceleration over the total time duration for the shock pulse. Figure 7 shows some shock forms with cushioning system applied for product-packaging systems.

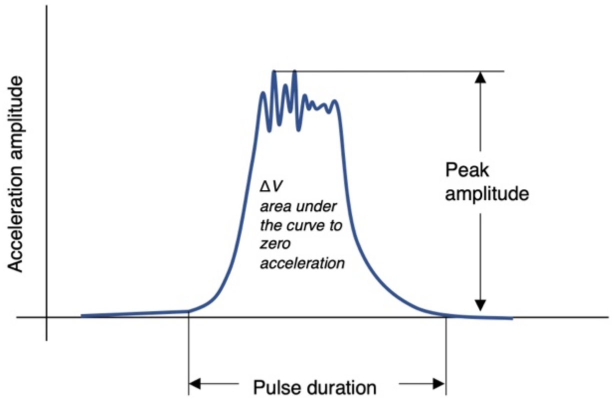


Figure 6. Standard impact shock pulse with its components

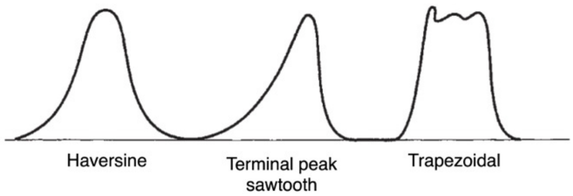


Figure 7. Typical shock waveform shapes with cushioning [23]

The rate of a change in the speed of an item when it impacts is called the acceleration rate (deceleration rate) of the observed impact event [21]. The acceleration rate of an impact can be expressed in *G* values, which are the dimensionless ratio between the acceleration in length per time square and the acceleration of gravity in the same measurement unit. With no cushioning, as in the case of collision of two rigid bodies, the acceleration values can reach 100 G. The acceleration levels depend on the duration of the impact pulse.

2.4 Data analysis

First, the recorded transshipment data from the shipping route was selected from all recorded events to choose only those that happened at transshipment locations. Then, the data were analyzed based on the acceleration level, duration, and velocity change in all three orientations. Furthermore, empirical Cumulative Distri–bution Functions (CDF) were developed using a two-parameter Weibull function to represent the charac–teristics of the distributions and show the percentage of occurrences below a given impact acceleration level. The Weibull distribution is a relatively simple pro–bability distribution in probability theory. Its CDF has two parameters, $\alpha > 0$ as the scale parameter and $\beta > 0$ as the shape parameter, as presented in eq. (1) below:

$$F\left(x|\alpha,\beta\right)=\int_{0}^{x}\beta\alpha^{-\beta}t^{\beta-1}e^{-(t/\alpha)^{\beta}}dt=1-e^{-(x/\alpha)^{\beta}} \quad (1)$$

3. RESULTS AND DISCUSSION

The findings suggest that most severe events were in the vertical direction, with 278 events over 0.5g. The vertical direction showed the most significant velocity and peak acceleration changes. This data highlights the importance of designing packaging systems to protect occupants from vertical impact shocks, which can cause significant injuries. However, it's worth noting here that 188 and 142 events were also recorded for the longitu–dinal and lateral directions, respectively, indicating that safety measures must be implemented in all directions to ensure the safety of the occupants.

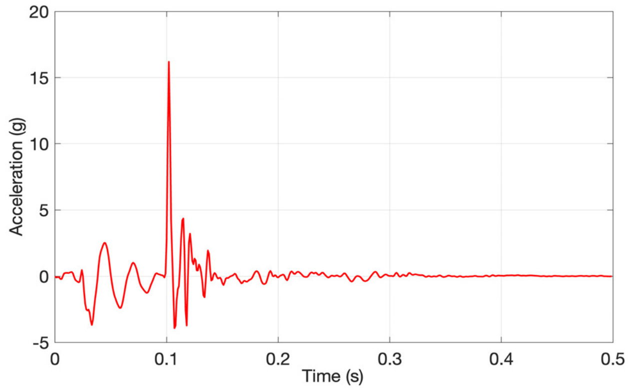
Figures 8a and 8b provide additional insight into the severity of the recorded events. Figure 7a shows the time history of the most severe events, indicating that the SAVER recorded multiple events with peaks above 10g, which is considered a very severe impact. Figure 7b shows the event with the highest velocity change, which also occurred in the vertical direction. This event recorded a 2.67g acceleration peak, less severe than other recorded events. Still, the velocity change was ex–ceptionally high, indicating a sudden and significant change in motion. This type of event can cause injuries such as whiplash or head trauma and highlights the im–portance of protecting occupants from sudden chan–ges in velocity, regardless of the magnitude of acceleration.

It's important to note that peak acceleration alone doesn't provide a complete representation of the shocks experienced during transshipment. The pulse duration, or the time it takes for the acceleration to reach its peak and return to zero, is also a critical factor, as presented in the last section. Figures 8a, 8b, and 8c visually represent the relationship between peak acceleration and pulse duration for all recorded events in all three orientations. Analyzing these plots shows a wide range of pulse durations for each peak acceleration level, indicating that shocks experienced during transshipment can vary significantly in duration.

Understanding the duration of shocks experienced during transshipment is crucial for designing packaging systems that can withstand the impact and protect the product inside. The interrelations between acceleration peak and pulse duration are well-known in the packa–ging testing industry. Figure 9 shows that typical impact durations during transshipment range from 2 to 68 msec in the vertical and lateral directions inside the container.

It's also essential to consider the type of product being transported, as some products may be more sen–sitive to specific shock durations or frequencies. By considering peak acceleration and pulse duration, pac–kaging designers can create more effective packaging systems that protect products from damage during transshipment.

The pulse durations recorded during vertical and lateral impacts had similar means, with a mean of 13.18 msec and 12.91 msec, respectively. These results suggest that the duration of shocks experienced during transshipment in the vertical and lateral directions are relatively similar. In contrast, the longitudinal direction had a higher mean pulse duration of 20.84 msec, indi–cating that shocks experienced in this direction can be more prolonged.



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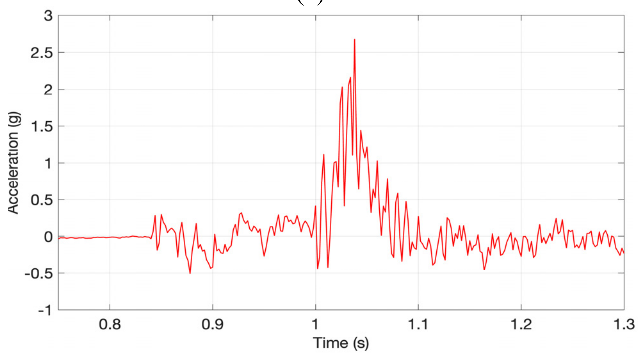
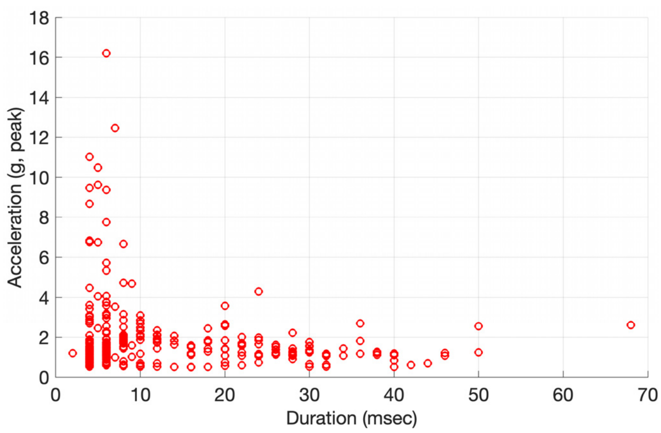


(b)

Figure 8. Acceleration time histories for a) highest accele–ration peak and b) highest velocity change

Interestingly, the longitudinal direction also had ten recorded events with a pulse duration above 100 msec, observed during rail transportation. These events were presumed to occur during the sorting of railway cars and were likely caused by hydraulic cushioning devices used in railcars. This finding highlights the importance of understanding the entire supply chain and the dif–ferent modes of transportation used.

The type and characteristics of shocks experienced during transportation can vary significantly depending on the mode of transportation, which can impact the packaging design and the product's ability to withstand shocks. Understanding these variations is essential for designing effective packaging systems that protect products throughout the supply chain.



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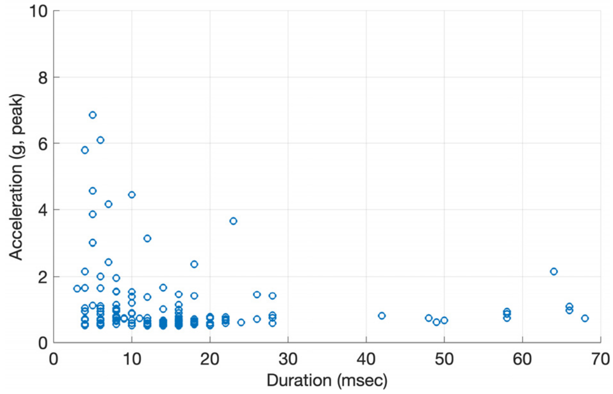

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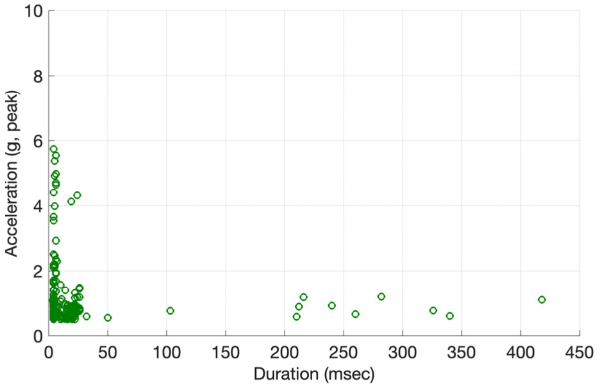


(c)

Figure 9. Acceleration peaks versus pulse duration for all measured impacts in all three orientations a) vertical, b) lateral, and c) longitudinal

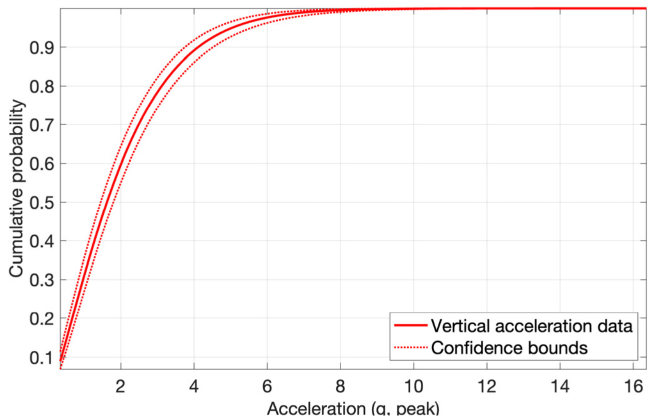
Figures 10a, 10b, and 10c depict the statistical occurrence of the measured peak acceleration values during transshipment events with Cumulative Distri–bution Functions (CDFs) in all three directions. The CDF plots provide valuable insights into the distribution of acceleration values, indicating the percentage of events below a certain acceleration level. The plots show that the vertical direction experienced the highest acceleration values, followed by the lateral and longi–tudinal direc–tions. These results are consistent with previous findings indicating that vertical shocks during transshipment can be more severe than those in other directions.

Additionally, the CDF plots reveal that the highest acceleration values were recorded at seaports when the containers were stacked on each other or in contact with the ground floor. This finding highlights the importance of proper stacking and securing containers during transshipment. Stacking containers incorrectly or placing them on an unsuitable surface can lead to high acceleration values, damaging the products inside.

Table 2 summarizes the statistical analysis results for the data, providing key parameters. The mean values indicate the average severity of shocks in each direction.

Table 2. Summary of acceleration data recorded for this study

	Mean (g)	Max. (g)	95%	80%
Vertical	2.42	16.20	6.65	2.29
Lateral	1.21	6.85	4.14	1.42
Longitudinal	1.14	5.75	4.02	1.39



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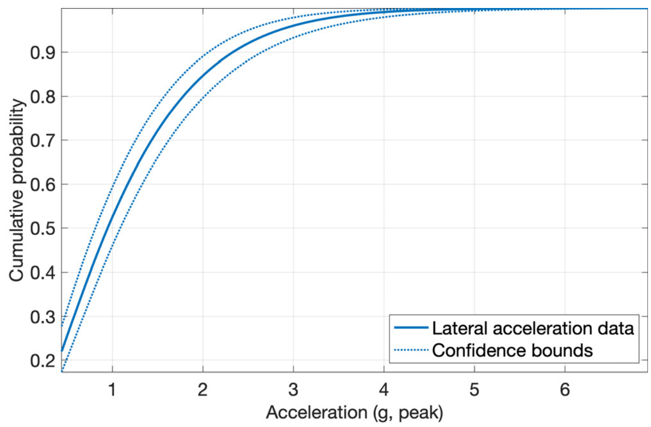

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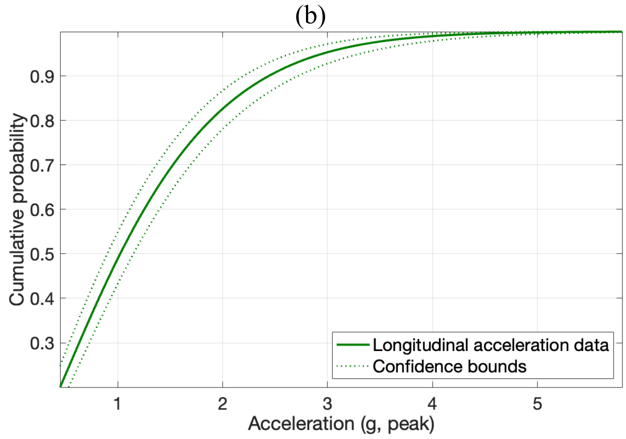


(c)

Figure 10. CDFs for a) vertical, b) lateral, and c) longitudinal data

Table 3 shows the statistical parameters of the distributions based on the Weibull best-fit regression analysis. The R-square values indicate the confidence level, with 1 representing 100%, for each fit in the three monitored directions.

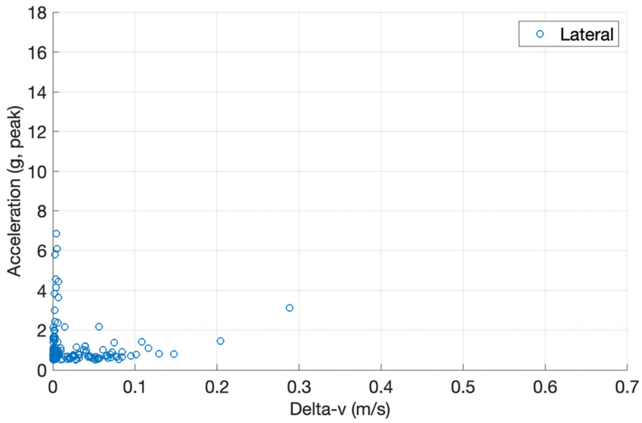
Table 3. Statistical parameters of CDFs on a best-fit regression

	Variance	α	β	RMSE
Vertical	2.42	2.15	1.29	0.02
Lateral	0.75	1.24	1.33	0.05
Longitudinal	0.79	1.33	1.38	0.11

While the acceleration data provides information on the intensity and duration of the shocks, the velocity change data offers a different perspective on the shock events that can occur during transshipment. High-velo–city changes can cause other types of damage that may not be reflected in the acceleration data alone. By providing statistical characteristics of velocity changes for the observed events, Table 4 contains the statistical data as an additional insight into recorded events that can occur during container transshipment. Figure 11 shows the acceleration peaks along their velocity changes.

The velocity change data can also be useful in designing packaging systems that can withstand high-velocity impacts and protect the products from damage. Overall, the combination of acceleration and velocity change data offers a comprehensive understanding of the shock environment during container transshipment and can inform the development of effective packaging solutions.

The data reported in this study can be directly used in any shock test platform to test larger items, such as unit loads distributed globally via multimodal conta–iners. Moreover, it is important to consider that the shock levels reported in this study are based on specific conditions and may not represent all container transshipment events. The shock environment can vary depending on con–tainer type, transportation mode, handling procedures, and loading conditions. Therefore, it is recommended that en–gineers and designers use caution when extrapolating the results of this study to other situations. More research may be needed to assess the shock environment under different conditions and develop packaging solutions that protect products from damage during container trans–shipment events.



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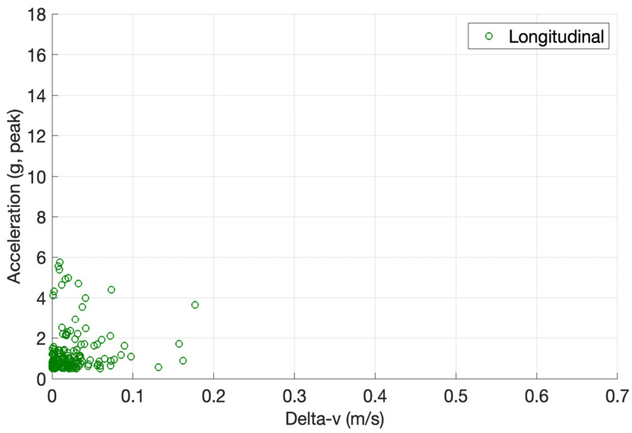

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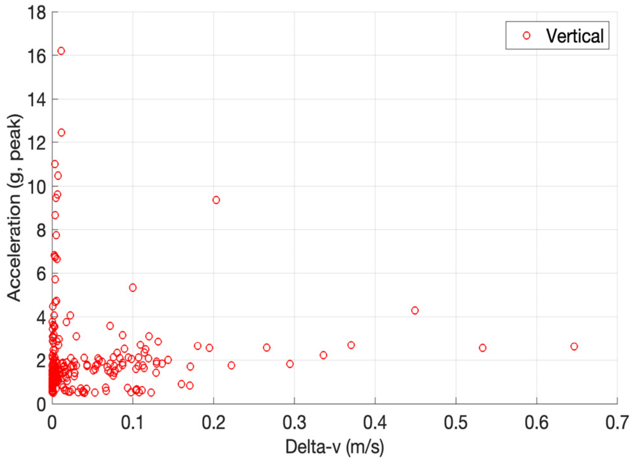

(c)

Figure 11. Acceleration peak versus velocity change for (a) vertical, (b) longitudinal, and (c) lateral events

Nonetheless, the data and analysis presented in this study provide a valuable starting point for understan–ding the shock environment during container trans–shipment. They can inform the development of packa–ging solutions that can withstand the rigors of global distribution.

However, it should be noted that determining and assessing the fragility or resilience of any packaged goods shipped by container should be based on its damage boundary region defined by pulse durations and acceleration peaks, below which the shipment remains usable or salable condition.

Table 4. Summary of velocity change values

	Mean (m/s)	Max. (m/s)	95%	80%
Vertical	0.06	0.65	0.17	0.09
Lateral	0.04	0.29	0.09	0.05
Longitudinal	0.02	0.18	0.08	0.04

2.5 Limitations of this study

1. This study does not examine the effects of the con–tainer load that could affect the shock levels. The payloads in this study were close to the maximum capacity of a normal container distribution.
2. The test standards generally apply safety factors for testing items during shock circumstances, so the field results can only be compared directly with test protocols with caution.
3. During intermodal container distribution, containers are sometimes exposed to extreme handling that can lead to significant shock levels. However, this paper did not record or present data on these events.
4. The study does not consider the potential damage that can be based on other stages of the supply chain or can come from the unique conditions of the container, such as former structural damages.
5. The study is based on data collected from a limited number of containers and may only represent part of the range of containers and products transported. The results may vary depending on the product type, container size, transportation mode, and other factors.

4. CONCLUSION

This study aimed to provide new and directly applicable information about shock conditions during multimodal container distribution. Shock resulting from observed container transshipment events was measured exten–sively across various locations. The levels of shock impact were generally higher in the vertical direction than those in the lateral or longitudinal directions. The most severe event occurred in the vertical direction with a peak acceleration of 16.20 G and a duration of 8 msec. The average acceleration level was 2.42g in the vertical axis with an average pulse duration of 13.18 msec, and a velocity change of 0.06 m/s. It was 1.21 g (0.04 m/s and 12.91 msec) in the lateral direction and 1.14 g (0.02 m/s and 20.84 msec) in the longitudinal direction. By under–standing the shock levels better, engineers can design packaging that can withstand these conditions and pro–tect the goods inside. The results of this study can also inform the development of testing protocols that accurately simulate real-world container transshipment events, ensuring that packaging is adequately tested before being used for shipping.

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ДОГАЂАЈИ УДАРНОГ ШОКА У МУЛТИМОДАЛНОМ ПРЕТОВАРУ КОНТЕЈНЕРА ЗА ТЕСТИРАЊЕ АМБАЛАЖЕ

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У савременим глобалним ланцима снабдевања, интермодална и мултимодална дистрибуција постала је суштинско средство транспорта. Комби–нација различитих видова транспорта је најчешће коришћена метода за дистрибуцију пошиљака између континената. Овај рад испитује и мери фи–зичке догађаје, као што су удар и удар, који се дешавају током транспорта ИСО контејнера дужине 40 стопа коришћењем више начина транспорта. Ови догађаји могу директно утицати на интегритет упакованих производа и узроковати штету. Студија се фокусира на догађаје као што су претовар и руковање контејнерима у чвориштима и терми–налима. Нивои ударних удара су посебно анали–зирани у свим тродимензионалним правцима, односно вертикалном, уздужном и бочном. Резул–тати показују проценат дешавања испод датог нивоа утицаја користећи статистичке карактеристике догађаја који су се десили. Величина и средња вредност нивоа убрзања, трајање импулса и промена брзине су такође пријављени.