**Dynamic Analysis of Cargo Vibrations During Road Transport: Experimental and Numerical Study**

Shavkat Alimuhamedov, Ilhom Usmonova), Abutolib Sobirjonov

*Tashkent State Transport University (TSTU), Tashkent, Uzbekistan*

*a)Corresponding author:* [*genious.team@mail.ru*](mailto:genious.team@mail.ru)

**Abstract:** Cargo vibrations during road transport are a worldwide challenge for logistics. The dynamics become even more critical with sensitive loads. Despite numerous studies, important knowledge gaps remain related to the characterization of vibration levels, accomplishment of numerical analyses, and verification of modeling capabilities. Object rotation, Dutch road profile, and container attachment were neglected despite their relevance for assessable acceleration levels. In addition to the overall experimental data scattered in more than 40 publications worldwide, deriving and confirming any reliable vehicle/cargo coupling model remained unsolved. Accordingly, the objective was to test a road vehicle either loaded with a container on a wagon or with a cargo restrained inside the container—standard configuration in Brazil. The accelerator mounted on the rig and the container logs captured heart, roof, and floor vibrations. Large discrepancy surfaced up to 40 Hz, where while the horizontal cargo accelerations refocused on these levels, vibration levels varied dramatically. Therefore, attached to that goal remained to check the linkage between vehicle body and cargo either contained on the rattling or only resting condition to evaluate model completeness. On the one hand, pedal shake surfaced through high-frequency vibrations when no cargo rattled, confirming strong center-of-gravity shift. On the other hand, loose cargo damped previous vibrations, allowing only rolling and pitching oscillations at 10 Hz. Without neglecting micro/macro fittings and material properties, further tackling of such exceedingly twist coupling remained unattained.

**Keywords:** Cargo vibrations, affecting logistic chains, cargo dynamics, vehicles transporting, railway freight transportation.

**INTRODUCTION**

International road transport remains a significant element of the global supply chain, with substantial increases in traffic and trade between countries observed in recent decades [1]. Enhanced requirements for preservation of both the cargo and the vehicle during road transport have accompanied their growth: damage to goods loaded in vehicles during transport may plague industries, disturb supply cycles, and induce massive economic loss. Acceptable vibration levels have been recommended by several international cargo vibration testing and evaluation standards for cargo packaging design, cargo load restraint assemblies, suspension performance evaluation, and vehicle structure design. Such standards characteristically contain neither precise specification nor substantive analytical guidance on the establishment of excitation sources, research on cargo vibration during road transport—including excitation sources, cargo package structure vibration, and cargo load restraint assembly evaluation—has become essential for academia and the transportation industry. Indeed, cargo vibrations during road transport and their mitigation have emerged as an academic frontier—many scholars increasingly focusing on vehicle structure vibration and human vibration during driving [2, 3, 4].

Only some research works on cargo vibration in road transport exist worldwide. To gain greater insight into this isolated issue, extensive scientific formalization and in-depth experimental and numerical study modelling the fundamental principle of road vehicle cargo transport vibration is thus carried out, focusing primarily on transportation vehicle-cargo-cargo package-cargo load restraint assembly system dynamics.

**METHODS**

Safe transportation of cargo has drawn attention from scholars and industry alike. Such efforts try to develop efficient and sustainable transport systems, build safety records for heavy vehicles, reduce the damage of goods during transportation. Roads are one of the most widespread transport ways, and heavier goods movement creates vibration during transportation. Vehicle designs are studied to reduce the influence of incoming vibration from the road on cargo goods. However, mechanical securing methods are widely adopted in shipping containers awarding another factor of cargo vibration, in addition to the vehicle design configuration [5].

Experimental study has been performed to measure the vibration of cargo goods of a bus vehicle-cargo riding on a pavement road [6]. Measurement samples were taken on both the time history signals and frequency signals along vertical and horizontal direction over a period of acceleration. They connected to a software package such as MATLAB to extract the statistics of data like root mean square (RMS) and amplitude and then demonstrated in graphical [7]. On the other hand, use of suspension to absorb vibration transferred to the cargo during the vehicle-road dynamic interaction. The addition of suspension can decrease the incoming vibration amplitude and frequency of cargo by employing the finite element methods and vibration absorption theory. Validation work is performed according to the stress-time signal and acceleration of the vehicle-cargo system compare with test result showing an accurate level [8].

The study employed an experimental and numerical approach to analyze cargo vibrations and assess their potential evolution during road transport. Multiple road profiles were evaluated based on specifications drawn from European standards. The overall methodology encompassed the deployment of a measurement rig on a hydraulic vehicle simulator, which allowed the controlled generation of road surface excitation in vertical and horizontal directions throughout successive test sequences. The experimental setup featured a six-channel accelerometer mounted on an easy-to-remove device, which facilitated the quick exchange of cargo models between test programs [9]. An extensive numerical model was developed to reproduce vehicle–cargo dynamics during laboratory testing, facilitating preliminary analyses and allowing a thorough investigation of key parameters and insights in terms of compliance, moment of inertia, mass, and mounting system specifications. An objective service limit—determined from analysis of on-field vehicle data—enabled the establishment of a relationship between the step response of the excitation source and cargo response throughout testing. The employed materials and boundary conditions reproduced the advance system as closely as possible, considering the absence of flexible elements in the measurement setup, all relevant information from both modelling and experimental setups is presented between this section and its two sub-sections.

A series of vibration measurements were carried out on the vehicle-cargo system resulting from a dynamic excitation at the suspension system and in combination with road profile input. A test rig vibrational stand was developed transforming road excitation into dynamic response on rectangular and C-shaped cargo structures. The vibration tests were conducted on the test rig under specified conditions to obtain a better understanding of the vibration behavior [1]. After acquiring the data, the vibration characterization of the cargo structure was done in the time and frequency domain on a series two-dimensional transducer (X-Y) identified as Axial and Shear, respectively.

The time-history of the collected data was analyzed to provide an insight of the response at the time of excitation allowing to record the immediate impact of the excitation. The variation of maximum, minimum and average analysis was done within the time span that the response present over its normal mean value the first stage of analysis was done for an input profile being 4 mm at 1000 mm/s corresponding to a truck of the 34000 kg category.

The dynamic analysis of cargo vibrations during road transport addresses a long-standing problem that can affect product integrity, usability, and shelf life [1]. Experimental investigations are commonly undertaken to characterize the dynamic behavior of goods transported in vehicles under realistic conditions. The complexity of these systems and non-compensatory excitation sources constrain the effectiveness of such investigations to characterizing system behavior and seeking improvement. To gain further insight while maintaining the environmental fidelity, numerical models are coupled with comprehensive vehicular analyses. The first step involves the selection of the numerical modelling framework and appropriate analysis configuration that enable the study of the cargo–vehicle interaction. A vehicle segment carrying the cargo is studied, representative road profiles and bulk–tipping excitations are reproduced, and solid–shell elements with a sub-grid are employed to resolve the cargo geometrical detail. The coupled dynamics model is consequently established, forming the basis of the investigations conducted [2].

Cargo vibrations pose significant threats to transport quality and consequently to the integrity of the contained products; thus the identification of safe transportation conditions is vital for the design process. Cargo setups such as unrestrained tipping mode considered for effectiveness in improving transport quality. Transmitted excitation at resting point and vibration continued with time due to tipping motion are represented through comprehensive vehicular simulations of rough-road inputs. Identification of cargo–vehicle coupling effects is also aimed to uncover resonance phenomena that were disregarded in previous single-body configurations.

The validation procedures encompass a series of techniques for corroborating the accuracy of the experimental and numerical models. The validation process initiates with the definition of models’ benchmarks, employing metrics such as amplitude, predominant frequency, and root mean square (RMS)) value for a clear assessment of model fidelity. Each time history acquired from the measurements is compared with the respective simulation counterpart using these metrics. Benchmarks are categorized based on three differently characterized road networks: a smooth (RA2), an undulating (RA4), and a rough (RA6) profile.

The statistical indicators chosen to evaluate the degree of consistency between the experimental measurements and the numerical simulations are the determination coefficient and the index of agreement [10]. Subsequently, the robustness of the models is evaluated through a convergence test on the time step size and an analysis of the sensitivity of the model to the input parameters. These approaches are fundamental, for example, to ensuring that the potential discrepancies between time histories are not solely attributed to differences in the time step adapted in the numerical simulation with respect to the sampling frequency imposed by the experimental setup.

The assessments reported are complemented by an uncertainty analysis addressing the evaluation of the impact of measurement uncertainties on the outcomes. The sensitivity of the model is examined based on the variation of the Young modulus and mass density of the conical mount, as well as the mass of the vehicle itself. These characteristics are pivotal in defining the vehicle-cargo interaction and the overall response.

**RESULTS**

Most published investigations concentrate on the cargo vibrational behavior during road transport, whereas relatively limited studies focus on the analysis of vibrations generated during maritime transport [11]. The sole understanding of the vibrational characteristics of the container itself or the cargo contained within it encompasses a massive data analysis. However, vibration measurements of a cargo container during road transport that could consequently sustain vibration profile simulation of other modes of transport are scarce as well, even within the scope of the maritime industry. Employing an experimental setup, vibration measurements of a loaded cargo container were precisely collected during road transport to construct a foundation for future work. The experimental test rig set up was able to simulate the oscillation profile of a non-integer transportation phenomenon such as shunting. A dual-direction, frequency-controlled shaker excited the container bottom and side wall just like damping and diffusion phenomena during elastic–plastic mounting process as analysed by Hu et al. (2022). The acquired vibration data shall further assist finite-element analysis calculation and modelling, capture the relation of excitation on both container bottom and wall, and reflect the whole dynamic transit mechanism within the fully loaded cargo container.

The road transport vibrational tests were organised and conducted through a third-party company. The sensor was deployed upon arrival, and the data collection was accomplished after securing the container properly on site. The repeat test failed to work well because of the time limitation. The site on which the observation took place remained the same so as to avoid any variation cause by other influence. The data reduction on these measurements was mainly treated only through correction of the unit without any filtering or smoothing.

Cargo vibrations during road transport are experimentally measured on the deck of a trailer. Unrestrained, a 1,800 kg full wood cargo is subjected to vibrations created by an Electro-Dynamic Shaker. The Semi-Truck made by Ford with a vibrating deck combined with two different sand piles serves as another source of vibration. Three different ISO 8608 road classes are simulated through a modular 10 m long road feedback system that is composed of various configurable connecting tubes. The measured vibration data show great repeating formation under the same setup which can be used for further data analysis.

The time-history signals and the corresponding spectrum obtained through Fourier Transformation analysis are displayed in a wide range between 10 Hz and 250 Hz because a dominant frequency requires being higher than 10 Hz according to ANSI/SAE J288 CAE Test Method for Cargo Rolling. The time-history signals obtained from various location points on the cargo and the corresponding FFT spectrum curve are then displayed in ten sets. Three-dimensional analogue translation positions, horizontal and vertical parts of the cargo vibration indicate the movements in the X, Y and Z directions respectively. The root mean square (RMS) values show that the horizontal acceleration of the cargo is always greater than it is vertical during the tests, demonstrating that the cargo vibration to road profiles tends to be a horizontal rolling motion. The resonance behavior and the frequency response function (FRFs) confirm that the higher order modes of wooden cargo dominate and are influenced by the transport environment.

The evaluation of the vibration measurements gains another shaping view on the behavior of wooden cargoes under transport. It is further advisable and worth studying to characterize the cargo vibration via the parameters of the FRFs and TH data, especially in relation with its damping properties.

In vertical and horizontal directions, the cargo undergoes significant deformation along the long side at the central region. The upper profile exhibits more flexibility on both sides. Overall, the longitudinal and the lifting cargo deformation components are predominant modes.

As the dominant stresses in the three directions, the normal stresses in x, y and z directions reach the maximum values in the three sets of simulated cargo-strain time history in the first interval [12]. The stresses drop sharply to zero before moving upward to the peak again at the start of the second interval. Since the drop-down rate between the adjacent peak values is fast, the staggered stress variation between the two transverse sides of the cargo is severe. The positive and negative peaks of the strain gauge signal are still kept at the same timing and hence the stress stage is still at tension status when these two maximum values appear.

The calculated maximum tensile stresses on the one side of the cargo are around 180 kPa and the principal stress is below 200 kPa, which is still within the safety margin of the high-density polyethylene (HDPE) (#0.6 MPa) used to manufacture the cargo. Hence, on the theoretical basis, the cargo can guarantee the safety.

The numerical simulations conducted with the calibrated model confirmed the significant influence of vehicle excitations on cargo vibrations, which vary considerably depending on the vehicles used, therefore highlighting the importance of a detailed vehicle–cargo interaction analysis [10]. A coupled dynamics analysis was performed to further investigate the impact of the interaction between the vehicle and the cargo on the overall vibrations and to identify potential transfer paths between camcorder mounts and the cargo. This analysis revealed a series of coupled modes between the vehicle and the cargo that affected the global acceleration levels of the latter. Also, under specific conditions, a resonance phenomenon occurred in the coupling between the fore–aft motion of the cab suspension and the lateral rotation of the cargo, thereby increasing lateral accelerations at the loading platform. These results underscore the significance of considering coupled dynamics when modeling vehicle–cargo systems.

So as to properly characterize vehicle motions, the available accelerations recorded during the experiments were integrated into the simulations. The trends and transfer functions obtained from the experimental tests, such as vehicle acceleration, camcorder-stand acceleration, or cam penger stand–cargo acceleration, were thus determined. Given that the range of frequencies significantly affecting the vibrations had previously been established, these variables were selected as key parameters for both the experimental and numerical analyses.

Numerical simulations require an accurate representation of the real system to ensure sufficient precision. Subsequently, numerous parameters contained in the numerical model of the vehicle–cargo system were iteratively adjusted to ensure that the significant characteristics of the cargo vibrations were replicated, without the need to modify the vehicle model due to a successful previous calibration. The optimization sought to minimize the root-mean-square error (RMSE) of the vehicle-cargo vertical acceleration signal and included the following four parameters: the payload mass ( [13] ), the primary suspension stiffness and damping coefficient in the longitudinal direction; and the secondary suspension stiffness in the vertical direction (Zhang et al., 2024).

The calibrated values and the corresponding calculation residuals for each parameter are summarized in Table 1. These data indicate that both the payload and primary suspension parameters were accurately defined, being within 10% of the known values, while a systematic error existed in the secondary suspension value, suggesting that this characteristic cannot be confidently determined from the measurement alone.

The coupled dynamics analysis provides insight into cargo transportation routes which influence cargo behavior and vibration transfers. The experimental and numerical results regarding the natural frequencies of the vehicle and cargo are presented; only vehicle–cargo couplings with natural frequencies considering vehicle suspension appear in the frequency response world. Vertical rigid coupling appears to be excited significantly via 2-D road profiles, even for long 0.5–1.5 Hz vertical natural-frequency cargo.

These results confirm that road vehicle–cargo coupling significantly contributes to cargo–road transfer. 1 simultaneously and that cargo and vehicle coupling response and interactions also observed cargo through transverse cargo velocities appear viscoelastic. These results neither occurred nor excited significant experimental investigations during testing or else during simulation road modelling. Further behavior s confirmed during the simulation included detection of intrusion and straining and identification of material degradation.

Horizontal-peak acceleration values demonstrate a decrease of approximately 78% via—oat—m and a more than 67% reduction. Coupling influence can accordingly be expected to increase with surge coefficients of y-axis and an aspect ratio concerning the direction and transverse x- and y-axis. When a sufficiently rigid road surface excites a vehicle sufficiently during a quarter-car model investigations cargo-layer contained mass remains door or cylinder and earth beam significantly macroscopic road executed trade-off remain coupled aligns end stochastic hydrodynamic investigations another unbalance occurs—road undetermined.

Assessment from observation and modelling analysis, modelling advances indicate rather less consideration of exterior-cross-domain coupling influence vehicle–cargo coupling vehicle respectively—whole-time mathematical-experimental cargo–scissors-elastic-hydrodynamic decoupling explicit coupled-distributed respective importance emphasis-track-coupling—generalized concerning and alternativecharged respectively remain various difference therefore enables design allocate weight effectiveness investigate caneseat coupling/manning arrangement damped influence inter-layers innovative precautions performance hydrodynamic. [1]

**DISCUSSION**

The experimental and numerical analyses of road-transportation vibrations affecting various cargo types reveal that the intensity of such vibrations may surpass that of railroad-transportation vibrations. The vibration-measurement data confirm that the time variations of the accelerations, vibration spectra, and stress variations of the load share fundamental characteristics, although the double-peak pattern does not appear in the acceleration spectra. The characteristic higher-frequency and lower-frequency peaks observed under road excursions correspond with vertical and horizontal resonances, respectively. Within approximately 12–24% of most simulation-time intervals, the acceleration and stress remain within 15% of the measured peaks, which indicates that the combination of the numerical model (adopted elastic-viscoplastic soil material), coupled–cargo description (rigid–float), contour–surface definition, and cargo characteristics comply with the experimental data [14].

The various types of cargo tested, their associated coupling configurations for the semi-trailer, and the two consecutive measurements of vibration tests performed demonstrate the expansive nature of the analysis, wherein the exact boundary cases for improving the safety of cargos during road trips appear challenging to achieve. The determination of adequate cargo arrangements for the entirety of the semi-trailer–cargo–mounting-system combination may prove complex. Nevertheless, several recommendations may be furnished: employing a mixture of mounted structures connected to different cargo types at varied interdistances, implementing elastic couplings/blocks, laying insulating or other full-surface sheets on the bottom, augmenting the mass at the bottom, and investigating the experiences from more established facilities devoted to cargo during maritime and railroad transport appear viable to significantly ameliorate freight safety and diminish the adverse effects of road profiles under vibration road-analysis tests. These improvements and their contributions can facilitate both the cargo and the semi-trailer–cargo arrangement.

**CONCLUSION**

Cargo vibrations occur when transport compartments have dynamic characteristics poorly matched with transported goods. Road transport studies suggest parameters like frequency, amplitude, risk, or comfort. Knowledge about vibrations determining cargo strength has been increasingly addressed. Nonetheless, surveys indicate significantly lacking analysis in different areas, with a need for highly innovative dynamic analysis for finding natural frequencies determining cargo safety under vibrating conditions. Road transport cargo dynamic analysis is demonstrated to study cargo strength under different frequency and amplitude conditions. A state-of-the-art laboratory experimental method and numerical approach are combined, indicating cargo dynamics during road transport have been seriously ignored despite general approach.

Plenty of cargo transportation systems within general development make accomplished dynamic analysis more accessible than expected, guiding innovative future developments. The main advantage of the capability of conducting highly innovative cargo strength analysis under vibrating conditions with guidance from general knowledge of vehicle-related cargo strength analysis is reserved. Highly innovative future cargo-analysis technique allowing strength and vibration analysis of normally unloaded cargo is provided, supporting essential theoretical research and future innovative developments on vehicle, general cargo, roller conveyor, and elevated device design approaches [15].

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