UNIVERSIDAD AUTONOMA DE NUEVO LEON

FACULTAD DE INGENIERIA MECANICA Y ELECTRICA

SUBDIRECCIÓN DE ESTUDIOS DE POSGRADO

"STANDARDIZED VIBRATION MODELLING FOR ELECTRIC HEAVY-DUTY TRUCKS: FROM FIELD DATA TO LABORATORY SIMULATION"

Por:
CARLOS CUAUHTEMOC NAJERA VILLARREAL

EN OPCIÓN AL GRADO DE:
MAESTRIA EN CIENCIAS DE LA INGENIERIA AUTOMOTRIZ

SAN NICOLÁS DE LOS GARZA, NUEVO LEÓN **11 DE OCTUBRE DEL 2025**

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Posgrado

Los miembros del Comité de Evaluación de Tesis recomendamos que la Tesis "Standardized Vibration Modelling for Electric Heavy-Duty Trucks: From Field Data to Laboratory Simulation", realizada por el estudiante Carlos Cuauhtémoc Nájera Villarreal, con número de matrícula 2173601, sea aceptada para su defensa como requisito parcial para obtener el grado de Maestría en Ciencias de la Ingeniería Automotriz.

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Abstract

This study investigates the characterization and standardization of real-world vibrational environments affecting electric heavy-duty trucks. The focus of the study is on the battery support structure, where vibrations from the road directly transmit to the battery cell structure and have an impact on the overall battery lifespan. By employing high-resolution accelerometers, extensive data were captured on a variety of test track scenarios, including urban, off-road, and highway conditions, providing a variety of scenarios that the vehicle can endure in its in-service time. The recorded vibrational signals were processed using Power Spectral Density (PSD) and Vibration Response Spectrum (VRS) methods, allowing the synthesis of representative spectral envelopes that reflect operational conditions with a high degree of statistical confidence. The research methodology encompassed both hardware deployment and advanced signal processing.

Data were acquired via enDAQ W8-D40 sensors, mounted directly on the vehicle chassis, and analyzed using MATLAB to construct statistical envelopes across multiple tests. These envelopes were found to align closely with established vibration standards such as MIL-STD-810H and ISO 2631-1, while capturing greater realism and dynamic range. A key outcome was the generation of GRMS-based vibration profiles tailored to specific use-cases, enabling more accurate simulation and predictive testing of lithium-ion battery behavior under mechanical stress. Having specific scenarios can lead to developers of battery structural supports to reduce time in the testing phase, since this data can accurately replace the in-life scenarios.

The findings provide a foundation for translating real-world data into laboratory simulations and simulation-based validation environments. Despite limitations in replication due to resource constraints, this work demonstrates the feasibility and value of integrating field-derived vibrational data into testing workflows. It ultimately contributes to the development of more robust, efficient, and safer electric vehicle components under operational stress by saving time and cost employed in the design phase that engineers experience when waiting for their prototypes to experience real-life scenarios.

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Content Table

List of Figures and Tables

Chapter 1: Literature Overview

1.1 Justification of the Project

Simulation-based real-world data is an invaluable tool in engineering and scientific research, particularly in areas such as the design of damping systems and the development of electric cells. However, researchers and designers need help accessing reliable data and the availability of suitable technologies for their processing and analysis. These challenges impede the precision and effectiveness of creating simulation models and limit the capacity to innovate and improve existing systems. This thesis project aims to overcome these barriers by implementing advanced methodologies for acquiring, processing, and analyzing field data, thereby creating more accurate and reliable simulation models.

The primary objective of this project is to bridge the gap between theory and practice, providing a robust foundation upon which subsequent studies and the development of technologies in these fields can be built. The project seeks to emulate the dynamic behavior of batteries subjected to vibrational conditions, considering the frequency spectra, amplitudes, and temporal patterns characteristic of actual operational conditions. This proposal is grounded in the premise that, through signal analysis techniques and dynamic modeling, it is possible to synthesize a vibration spectrum that captures the complexities inherent to the operational environment of batteries, including responses to random, transient, and harmonic vibrations.

Applying real-world data in simulation models represents a significant step forward in automotive engineering. It allows for the development of theoretically sound and practically viable designs, thereby reducing the gap between laboratory testing and real-world performance. By focusing on the conditions electric vehicle components experience, this project aims to produce meaningful and directly applicable results to real-world scenarios.

The added value of this thesis is improving the accuracy of simulations using real-field data. By doing so, the project will pave the way for improving damping systems and the structural design of electric cells, contributing to the advancement of electric vehicle technology. This will support the broader goal of achieving more sustainable and efficient transportation solutions in the context of the ongoing energy transition.

Understanding the impact of vibrations on electric vehicle (EV) battery performance is important for ensuring the longevity and reliability of lithium-ion batteries. Vibrations can cause mechanical and electrical degradation, ultimately affecting battery efficiency and safety. This chapter provides an overview of the existing literature on vibration analysis in the context of EV batteries, emphasizing key regulatory standards, prior research, and testing methodologies that have been employed to assess battery durability under vibrational stress.

A portion of vibration testing for lithium-ion batteries is guided by international safety regulations, particularly the UN 38.3 T3 standard. This regulation ensures that lithium-ion batteries can pass vibrations encountered during transportation without compromising safety or performance. However, the standardized sinusoidal waveforms used in the test may not fully capture the complex vibrational stresses experienced in real-world applications, such as those found in heavy-duty electric trucks. Additionally, the IEC 62660-2 standard provides further insights into battery performance, but it primarily focuses on electrical and thermal factors rather than mechanical stresses induced by vibrations.

Previous research has explored the mechanical and electrical degradation of lithium-ion batteries due to vibrational stress. Studies done by Hooper et al. and Zhang et al. [1] have demonstrated that long-term exposure to vibrations influences battery material stability and performance. Advanced methodologies such as Parametric Reduced-Order Models (PROMs) and multi-axis vibration testing have been developed to simulate real-world conditions more accurately. The research by Eager[2] et al. further supports these findings by examining the effects of vibrations on passenger comfort in public transportation, providing valuable insights into how vibration dynamics influence vehicle components.

This chapter lays the foundation for the research presented in this thesis by reviewing key regulatory standards, experimental methodologies, and previous studies on vibration analysis in lithium-ion batteries. Addressing the limitations of current standards and incorporating real-world testing data into vibration modeling will provide valuable insights for improving battery design and performance in electric heavy-duty vehicles.

1.2 Introduction

1.3 Regulations used in vibration analysis

Vibration analysis is a key aspect of understanding the impact of vibrational forces on electric vehicle (EV) battery performance. Vibration-induced stresses can lead to material degradation and performance deterioration in lithium-ion batteries, which are increasingly used by OEMs. The study of vibrations is essential for predicting the longevity and reliability of these batteries, as vibrations can accelerate wear and affect both mechanical and electrical properties.

As part of the United Nations regulations for the transport of dangerous goods, the UN 38.3 T3 standard has been developed specifically for lithium-ion batteries. This test ensures that lithium-ion batteries can withstand the vibrations and shocks encountered during transportation without posing a safety risk. The "T3" part refers to the specific vibration testing procedure in the UN 38.3 standard, which simulates the vibrations that batteries might experience during handling and transit.

In the T3 test, the battery or battery pack is subjected to sinusoidal vibrations within a specific frequency range, typically from 7 Hz to 200 Hz. The test aims to determine whether the battery can endure these vibrations without leakage, venting, rupture, or fire. The procedure involves applying a range of accelerations, from 1 G up to 8 G, depending on the frequency, and testing in all three axes (X, Y, and Z) [3]

The UN 38.3 T3 test lacks real-world representativeness using sinusoidal waveforms that are standardized and may not fully replicate the complex, irregular vibrational patterns encountered in operational conditions such as those found in electric vehicles. This might lead to discrepancies between test results and the actual performance degradation observed over time in the field. This project can address these limitations by ensuring that higher frequencies and variable accelerations are directly influenced by the truck's response to the environment it is crossing. Long-term testing is also a key addition to the T3, as it primarily focuses on short-term stress, designed to ensure safety, but does not fully simulate the cumulative effects of vibration over the battery's lifespan.

Some other tests are used when evaluating battery performance, which is important to mention in this thesis. The IEC 62660-2 standard is part of the International Electrotechnical Commission (IEC) guidelines that focus specifically on the testing of rechargeable lithium-ion battery cells used in electric vehicles (EVs) and hybrid electric vehicles (HEVs). This standard is critical for assessing the mechanical, electrical, and thermal stresses that these batteries experience over time.

A key focus of the IEC 62660-2 standard is to evaluate the cycle life and capacity retention of lithium-ion cells under repeated charge and discharge cycles. These tests simulate the typical conditions that a battery might face in a vehicle, ensuring it can meet the demands of real-world driving conditions. It also examines the battery's charge/discharge performance, testing its ability to maintain stable output and charging efficiency over time. The standard sets the required conditions for these tests, including temperature, charge rates, and other environmental factors that can influence battery performance, such as humidity and vibration. [4]

While other standards like the UN 38.3 or UL 2054 address general transport and consumer safety, IEC 62660-2 is designed to guarantee that automotive batteries can perform reliably and safely throughout their operational life in vehicles.

The IEC 62660-2 standard concerns the performance and reliability testing of lithium-ion battery cells used in electric vehicles (EVs), focusing on long-term cycle life, capacity retention, and electrical performance under various operational conditions. The tests defined in IEC 62660-2 aim to evaluate the electrical and thermal performance of batteries over extended use, simulating real-world vehicle operation. However, this standard does not directly address the vibrational impact on batteries, which is the central theme of this thesis.

This research focuses on investigating the vibration-induced degradation of lithium-ion batteries in electric heavy-duty trucks. Mechanical and electrical effects of vibration exposure in a real-world, long-term operational context, including the cumulative effects of vibrations that occur over time. The IEC 62660-2 standard does not specifically account for vibrational stresses or simulate the environmental vibrations that batteries experience during vehicle operation or transport. Instead, it emphasizes electrical tests and thermal conditions, which are crucial for understanding battery performance but do not fully address how vibrations affect battery longevity or mechanical integrity.

While both approaches aim to ensure battery reliability, this research expands on the limitations of IEC 62660-2 by integrating real-world vibration data collected from test tracks and electric trucks. The IEC 62660-2 standard evaluates batteries in static or simplified dynamic conditions, whereas this work incorporates complex vibrational profiles and seeks to replicate the actual environmental conditions of electric truck operations.

1.4 Research Hypothesis

Capturing vibrational data under various driving conditions enables the synthesis of standardized spectral profiles. These profiles can be utilized for theoretical design, experimental validation, and optimization of battery support structures in medium-duty electric trucks. By ensuring that laboratory simulations and tests accurately reflect real-world conditions, this approach enhances the reliability and effectiveness of vehicle component evaluations.

1.5 Problem Statement

In developing and evaluating heavy-duty electric vehicles, there needs to be more unified standards for measuring and quantifying the impact of vibrations on these complex systems. This absence of standardized criteria complicates the comparability and replicability of results obtained from different studies. It limits the ability to design effective engineering solutions that enhance the resilience and durability of these vehicles under adverse conditions. Considering this issue, this thesis proposes implementing an innovative methodological approach that captures vibrational data directly from a test track using an actual vehicle model. This approach aims to establish a reference database of vibrations that accurately reflect operational conditions and can be reproduced in controlled environments, such as laboratories or specialized vibration test benches.

These measurements will be collected using available technology, including high-precision accelerometers and software for data processing and analysis, as well as specialized computer-aided design tools for simulating operational scenarios. This procedure will enable the characterization of the spectrum of vibrations to which heavy-duty electric vehicles are subjected during operation. Still, it will also provide critical data for the engineering process and structural and component improvement design. By basing these enhancements on actual and rigorously analyzed measurements, it is anticipated that significant advances can be made in optimizing the performance, safety, and longevity of these vehicles, thereby contributing to the sustainability and efficiency of freight transport in the current context of the energy transition.

The use of direct vibrational data collection from test tracks, as proposed, is intended to address the current gap in standardized testing methodologies for heavy-duty electric vehicles. By implementing a robust, data-driven approach, it is possible to develop a comprehensive understanding of how these vehicles behave under various operational conditions. This understanding is vital for informing the design and development of more resilient and durable suspension systems, ensuring heavy-duty electric vehicles' safety and performance.

This thesis aims to advance the field by providing a solid foundation for developing unified standards and testing methodologies for heavy-duty electric vehicles. Doing so will enhance these vehicles' durability, safety, and performance, ultimately supporting the transition toward more sustainable and efficient freight transport solutions.

1.6 General Objective

To develop a detailed and accurate vibration profile for the battery support structure, advanced technology, such as high-precision accelerometers and specialized signal processing software, will be utilized to establish a standardized model that can be reliably reproduced in controlled laboratory environments.

1.7 Specific Objectives

1. Utilization of an Existing Test Track and Real Road

Conduct tests on the electric vehicle's battery support structure across various vibrational scenarios, utilizing the existing test track and an actual road. The analysis will define track conditions, driver behavior, and the vibrations generated under typical truck operation, ensuring the data reflects real-world conditions.

2. Selection of Accelerometer Placement and Mounting Method

Determine the most effective locations on the vehicle for placing accelerometers and select the optimal methods for securing these devices. The focus is to ensure that adhesion errors between the accelerometers and the truck chassis do not compromise vibration measurements. Good placement and secure mounting are essential for obtaining accurate, reliable data and supporting the validity and repeatability of the vibration measurements.

3. Signal Processing Using Advanced Software

Use advanced software tools to process the vibration signals collected from field tests. This step involves filtering out potential noise and contamination caused by the vehicle's inherent operational vibrations, ensuring the data reflects actual operational conditions. The software will also merge various data sets, creating a comprehensive database of vibration profiles that can be replicated in a controlled laboratory environment for further analysis and testing.

1.8 Thesis Structure

Chapter 1: Literature Review

This chapter explores previous studies on vibration analysis, battery performance in heavy-duty electric trucks, and advanced methods for field data acquisition and simulation. It emphasizes the limitations of current random vibration testing approaches and highlights the advantages of field data-driven methodologies for laboratory replication. Additionally, this chapter outlines the thesis structure to ensure a coherent presentation of the research objectives, methodologies, and findings, facilitating an in-depth understanding of the study.

Chapter 2: Introduction

This chapter provides an overview of the research problem, focusing on the role of real-world vibrational impacts on the efficiency and durability of electric vehicle batteries. It defines general and specific objectives, introduces the hypothesis that standardized vibration profiles can enhance component testing reliability, and outlines the study's relevance within the automotive field.

Chapter 3: Methodology

A description of the experimental approach this chapter explains the use of high-precision accelerometers for capturing real-world vibration data on existing test tracks and public roads. It discusses the criteria for sensor placement and secure mounting to avoid measurement inaccuracies. Advanced signal processing techniques are described, highlighting methods for noise filtering, data integration, and the creation of a replicable vibration database.

Chapter 4: Results and Analysis

This chapter presents experimental results, including the measured vibration profiles and their laboratory-based application. The analysis focuses on the accuracy of the derived profiles in mimicking real-world conditions and evaluates their potential to replace conventional test procedures in battery durability studies. Comparisons between field data and simulation outputs are critically examined.

Chapter 5: Conclusions and Recommendations

The final chapter summarizes the key findings, reinforcing the feasibility of field data-driven vibration testing as a reliable alternative to traditional methods. It discusses the implications for suspension and battery system design in electric trucks and proposes recommendations for refining the methodology in future research, including expanding its application to other vehicle components.

Chapter 2: Background theory

2.1 Introduction

The development of electric vehicles (EVs) has progressed rapidly in recent years, driven by advancements in battery technology, government regulations, and growing concerns about environmental sustainability. Unlike conventional internal combustion engine vehicles, EVs rely entirely on electric power, making them quieter and more efficient. However, this shift also introduces new engineering challenges in vehicle dynamics and durability. The impact of road vibrations on battery performance and vehicle reliability has become a critical area of study. Understanding these factors is essential for improving EV longevity and safety.

One of the key components influencing ride quality and durability in EVs is the suspension system. Traditional vehicle suspensions are designed to manage the effects of road irregularities, giving passenger comfort and protecting vehicle components from excessive stress. In EVs, suspension systems play an even more significant role due to the weight and structural sensitivity of battery packs.

Accurate data collection is fundamental to understanding the effects of road-induced vibrations. Accelerometers, which measure acceleration forces, are widely used in automotive testing to monitor vehicle responses to various driving conditions. These sensors provide detailed insights into how different components react to vibrations, enabling engineers to develop more robust suspension designs

Traditional approaches, such as standard vibration tests and component-level durability assessments, provide useful information but often fail to capture real-world driving complexities. Modern techniques like Road Load Data Acquisition (RLDA) offer a more comprehensive approach by collecting data from vehicles operating under actual conditions. This method allows engineers to develop more accurate predictive models and refine suspension designs based on real-world performance.

Finite Element Analysis (FEA) further enhances the study of vehicle vibrations by simulating how different structural components respond to external forces. This computational method enables researchers to analyze stress distributions, deformation patterns, and potential failure points in suspension and battery systems. When combined with RLDA, FEA provides a powerful toolset for improving EV design, ensuring that vehicles can withstand the diverse and often unpredictable conditions encountered during operation. This chapter explores these key areas in detail, establishing the foundation for the methodologies used in this research.

2.2 Background on Electric Vehicles (EVs)

Technology evolves to create a smaller carbon footprint and reduce the environmental impact of CO2 emissions generated by humanity. This race against time has encouraged newer generations to use increasingly cleaner and renewable energy sources. While the creation of the electric vehicle dates back to 1834 with the implementation of photovoltaic cells powering a carriage designed by the Davenports in the United States of America, the first commercially recognized electric vehicle is attributed to the famous French car manufacturer Peugeot in 1941 with the VLV, stood for Voiture Légère de Ville (Light City Car) which had a range of up to 80 km and a maximum speed of 36 km/h [5].

This set the stage for automotive engineers and designers to begin the race to enhance the technology of such vehicles, initially to make them more appealing to potential customers. Today, the goal is not only to innovate to gain a larger market share but also to reduce the impact caused by emissions from internal combustion engine vehicles, which have been the predominant model for consumers since Thomas Ford invented the first commercial vehicles around 1908. [6]

Electric vehicles are becoming increasingly common in cities and on highways. According to the latest report from the World Economic Forum, one in seven cars is powered by rechargeable photovoltaic cells, with an estimated 10.6 million such vehicles. Following a global pause in vehicle manufacturing due to the COVID-19 pandemic, the development and research of EVs (Electric Vehicles) has been further accelerated. EVs now hold a majority share in markets like China, representing 25% of the national market. [7]

This is due primarily to China's need to reduce its carbon emissions, as it has been considered one of the largest producers of CO2 and greenhouse gases globally since 2008. As a nation traditionally relying on fossil fuels such as coal, oil, and petroleum, the expected shift towards improved mobility for Chinese citizens is promising [8].

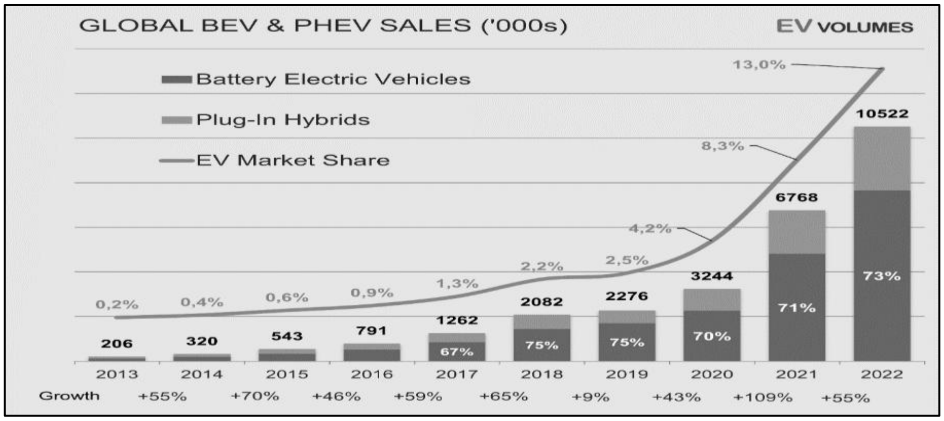

Figure 1. Adapted from "Evolution of sales of electric vehicles worldwide," by M. Moultak, N. Lutsey, & D. Hall, 2022, International Council on Clean Transportation (ICCT).[8]

One sector that also promises to impact this electrification significantly is heavy-duty vehicles, commonly known as buses or trailers. These vehicles' primary purpose is transporting heavy loads or covering long distances, carrying goods. In past years, electrifying this class of vehicles was considered out of reach, as the distances and range these vehicles would need were beyond the capabilities of power cells. These cells differ from traditional ones due to their high energy density and must be recharged using higher amperage currents than conventional electric vehicles.

Technology in this sector for electric vehicles has not advanced as quickly as stakeholders would prefer, raising doubts about the feasibility of electrification projects. Many of the major Original Equipment Manufacturers (OEMs) have decided to establish technological disclosure agreements, as the heavy lorry sector works closely with its competitors. Large companies such as Volvo have taken the lead in developing these types of technologies and have created a model of agreement between clients, companies, and stakeholders to disseminate the latest advances in the industry and encourage potential customers to support these initiatives [9].

Medium or heavy-duty vehicles powered entirely by rechargeable electric cells are now a reality. These vehicles share characteristics with current electric vehicles, featuring multiple electric cells that power electric motors distributed throughout the truck's chassis. This configuration provides greater torque and produces zero carbon emissions. The arrangement of these motors varies depending on the manufacturer and the truck's intended use. The most common configurations include one motor on each axle, a front and rear motor, and, in some prototypes, even a motor for each wheel. The type of cell used can vary in chemical composition based on the materials used in manufacture, with lithium, nickel, and lead being the most common.

Heavy-duty electric trucks are a technology developed out of necessity to reduce carbon emissions in the automotive sector. Heavy-duty trucks represent less than 10% of all vehicles yet contribute up to 40% of carbon emissions. Multiple barriers have been reduced to implement less environmentally harmful options, such as the lack of charging infrastructure, the need for long-distance travel for goods transport, legal restrictions on allowable weights for heavy-duty vehicles, and others [10].

Many well-known vehicle manufacturers and new startups are now actively developing zero-emission vehicles for medium and heavy loads. Several of these companies have advanced to small- and medium-scale production, reflecting a significant shift in the industry. Among the prominent Original Equipment Manufacturers (OEMs) involved in this field are Daimler, Tesla, Toyota, and Navistar International, now part of the TRATON Group. The surge in the production of heavy-duty electric vehicles has intensified pressure on governments to invest in and establish the necessary infrastructure to support these vehicles and make them viable options for consumers.

The key characteristics of these heavy-duty electric vehicles are noteworthy. Firstly, they offer zero exhaust emissions. Unlike their fossil fuel counterparts, electric trucks do not burn any fuel, avoiding polluting gas production and presenting a highly environmentally friendly alternative. This feature makes them particularly attractive compared to traditional diesel-powered ones. Secondly, batteries and electric motors are fundamental to these vehicles. The batteries are the core component, storing and distributing energy to the engine or motors that propel the vehicle. These components are configured in series or parallel to adjust voltages and amperages according to the vehicle's requirements.[11]

In addition, electric vehicles provide lower maintenance costs. Traditional vehicles often require expensive maintenance for emission treatment fluids, diesel engines, and components such as turbochargers and air filtration systems, contributing to higher maintenance expenses. In contrast, electric vehicles require only predictive maintenance and monitoring of battery voltage levels, which is a significant advantage for fleet owners. Lastly, electric heavy-duty vehicles deliver instant torque, which is crucial for navigating rough roads and uneven terrain while transporting goods efficiently. Traditional routes are only sometimes well-suited for vehicles carrying heavy loads, often involving challenging inclines. Electric cars, however, benefit from the immediate generation of energy in their motors, allowing them to handle steep gradients and easily maintain efficiency in their operations.

2.3 Importance of Suspension Systems in EVs

When designing suspension systems for electric vehicles, avoiding resonance at the typical natural frequencies of various components is crucial. The vehicle and sprung mass combination fluctuates between 0 and 7 Hz, while the powertrain and gearbox typically operate within the 7 to 20 Hz range. The vehicle's chassis system also resonates between 20 and 40 Hz [12]. By avoiding these frequencies, the lifespan of the battery system can be significantly extended, and the likelihood of exothermic reactions can be diminished.

It has been reported that several factors can affect the reliability of lithium-ion battery packs, many of which can originate during the manufacturing process. Of these, the most critical are chemical factors, including impurities and concentrations in battery chemistry, and the procedures for joining materials, such as processing and cell closures, whether hermetic or crimped. Moreover, in the long term, the environmental conditions under which a battery pack operates (such as ambient temperature, pressure, mechanical and thermal shock, and mechanical vibrations) play a role in determining battery reliability. The strategic placement of the battery pack within an electric vehicle can also enhance the efficacy of the battery packaging design in addressing these issues.

The suspension system in electric vehicles is not just about ensuring safety, comfort, and overall performance. It also plays a crucial role in managing the additional weight of the battery packs, which are typically positioned low and across the vehicle's floor. This unique weight distribution demands a robust suspension system that can maintain stability under various driving conditions.

One of the primary functions of a suspension system is to support the vehicle's weight, manage its balance, and provide a smooth ride. In EVs, this role becomes even more critical due to the heavier batteries that increase the vehicle's overall mass. The suspension system must handle this added weight without compromising vehicle dynamics, such as braking efficiency, acceleration, and cornering. Inadequate suspension designs can lead to increased wear on tires and other components, reducing the vehicle's lifespan and increasing maintenance costs. [13]

Moreover, the suspension system must be capable of managing the unique torque characteristics of electric motors. Electric motors deliver instant torque, significantly stressing the vehicle's structure and suspension components. A well-engineered suspension system helps distribute this torque evenly, enhancing the vehicle's handling and stability. This is particularly important for EVs, as maintaining control during rapid acceleration and deceleration is critical to providing a safe and enjoyable driving experience. [14]

In addition to managing weight and torque, the suspension system plays a vital role in energy efficiency. By effectively damping vibrations and reducing unwanted movements, a sound suspension system helps minimize energy loss, extending the vehicle's range, which becomes critical for EVs. Advanced suspension systems that adapt to changing road conditions and driving styles can further optimize energy consumption, making EVs more efficient and appealing to a broader audience.

2.4 Introduction to Accelerometers and Data Collection

In automotive engineering, accelerometers are indispensable for testing and analyzing a vehicle's dynamic responses under various conditions. These sensors function by gauging the rate of change in velocity over time, thereby providing crucial data on vibrations, accelerations, and other dynamic forces. They facilitate a deeper understanding of how a vehicle's suspension and other components respond to real-world scenarios and significantly enhance vehicle performance. Their data informs design decisions that can make a real difference on the road.

In testing, accelerometers are frequently mounted on various vehicle parts, such as the chassis, axles, and body, to collect precise data on vibrations and accelerations. Their role in understanding and improving vehicle performance is significant. For example, when accelerometers are affixed to the chassis of a heavy vehicle (HV), they can measure body-bounce and damping ratios with experimental accuracy. Similarly, accelerometers installed on the axles can ascertain axle-hop frequencies, analyzing the dynamic forces acting upon the wheels. These measurements enable engineers to evaluate the effectiveness of the suspension in mitigating vibrations and maintaining vehicular stability. [15]

Accelerometers also play a critical role in collecting field data during road tests, capturing intricate details about how suspensions react to various road conditions. By recording accelerations across three axes, accelerometers can comprehensively profile the vehicle's dynamic behavior, providing engineers with a deep and thorough understanding of the vehicle's performance. Such detailed data collection is invaluable for developing and adjusting suspension systems that are better equipped to handle the unique demands of heavy electric vehicles.

The utility of accelerometers extends beyond the mere measurement of vibrations; they are also integral in determining the inertial forces exerted by unsprung masses, such as wheels and axles, on a vehicle. For example, when accelerometers are mounted on HV half-axles between strain gauges and the hub, they can measure the dynamic inertial loads from the unsprung masses. This data is essential for accurately reconstructing wheel-force histories and understanding the impact of these forces on overall vehicle dynamics. Researchers can obtain a more holistic view of the forces acting upon a vehicle by combining accelerometer data with strain gauge measurements. This leads to improved suspension designs and enhanced vehicle performance.

Accelerometers provide detailed data on vibrations, accelerations, and other dynamic forces. Their capability to measure both sprung and unsprung mass movements and inertial forces makes them essential for understanding the complex interactions between a vehicle's components under real-world conditions. By capturing precise field data during road tests, accelerometers aid engineers in developing more robust and efficient suspension systems, ensuring vehicles are well-prepared to handle various road conditions. As automotive technology advances, the role of accelerometers in testing and analysis will only become more pivotal, driving further progress in vehicle design and performance.[16]

2.5 Traditional Methods of Testing Suspensions: Accelerometer

Accelerometer measurements are a technique in suspension testing. Accelerometers measure acceleration forces, which can be static, like the constant force of gravity, or dynamic, caused by movement or vibrations. They are typically mounted on different vehicle parts, such as the chassis, axles, or wheels, to capture data about how the vehicle responds to various road conditions. By analyzing the data from accelerometers, engineers can determine the frequencies at which different vehicle components resonate and assess the performance of the suspension system in damping these vibrations.

These devices are especially useful in capturing high-frequency vibrations when a vehicle encounters rough terrain or road imperfections. For instance, accelerometers placed on the chassis can provide insights into body-bounce dynamics. These are crucial for understanding how well the suspension system isolates the vehicle's occupants from road shocks. Similarly, accelerometers mounted on the axles can help identify axle-hop frequencies, which indicate how well the suspension maintains wheel contact with the ground, a critical factor in vehicle stability and handling.[17]

Advanced accelerometer setups might include multiple devices positioned along different axes to capture three-dimensional motion. This allows for a comprehensive analysis of the suspension system's performance across various directional inputs, such as vertical, lateral, and longitudinal accelerations. By examining these data points, engineers can create a detailed profile of how the suspension system responds to dynamic forces, which is invaluable for optimizing comfort, safety, and performance. [18]

2.5.1 Strain Gauge Testing

Strain gauge testing is another method used in suspension testing. It measures the strain, or deformation, of suspension components under load. A strain gauge is a sensor that detects minute changes in length when a material is subjected to stress. Applied to vehicle suspension, strain gauges are typically attached to critical points on components such as control arms, springs, and shock absorbers.

The primary goal of strain gauge testing in suspension systems is to thoroughly measure various parts' stress distribution and deformation when the vehicle operates. This comprehensive approach is essential for understanding how the suspension reacts to different loads, whether from road conditions, cornering forces, or braking. By analyzing the strain data, areas of high stress can be identified, which could lead to material fatigue or failure over time, providing reassurance about the system's robustness.

Strain gauges validate computer models and simulations of suspension behavior. By comparing real-world strain measurements with predicted values from finite element models, engineers can assess the accuracy of their simulations and make necessary adjustments. This is important for designing lightweight suspension components, where material strength and fatigue resistance are critical considerations. Engineers might use strain gauges to evaluate the impact of varying spring rates or damping settings on stress distribution within the suspension. This allows for fine-tuning the suspension to achieve the desired balance between comfort, handling, and durability, empowering engineers to make informed decisions. By correlating strain data with acceleration and displacement measurements, engineers can gain insights into how different forces and motions interact within the suspension system, leading to more effective design and optimization strategies.

2.5.2 Shaker Table Testing

Shaker table testing, also known as vibration testing, is a controlled laboratory method used to evaluate the performance of suspension systems under simulated road conditions. In this method, a vehicle or a suspension system component is placed on a platform that can move in various directions and varies in its degree of freedom, replicating the vibrations and shocks that a vehicle might experience on different types of roads.

The precision of shaker table testing is unparalleled, providing repeatable and controlled conditions that are ideal for isolating specific variables and understanding their effects on suspension performance, but also highly practical. By fine-tuning the frequency and amplitude of the vibrations, designers can accurately simulate various road conditions, from smooth highways to bumpy off-road trails. This meticulous evaluation process allows for identifying weaknesses and areas for improvement in the suspension system, instilling confidence in the results.

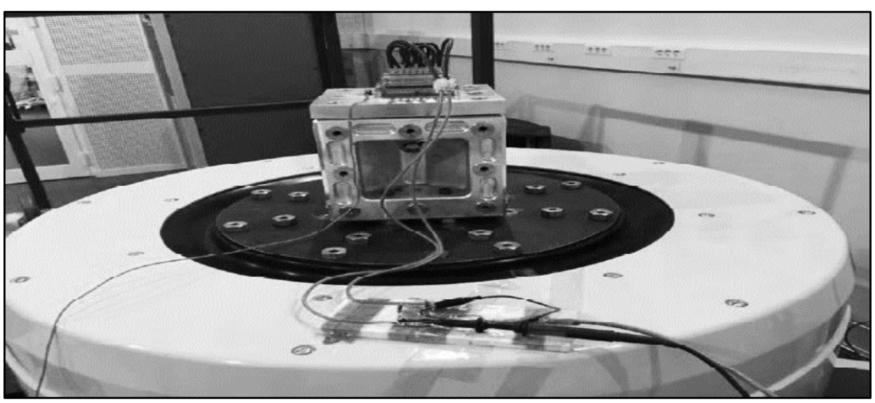

Figure 2. Example of vibration testing on a shaker table. Image from ALTER tech.

Shaker table testing is crucial in assessing the damping characteristics of shock absorbers and springs. These components are pivotal in controlling vehicle motion and ensuring a comfortable ride.

Engineers can measure their ability to absorb and dissipate energy by subjecting them to controlled vibrations, essential for minimizing body roll, pitch, and bounce.[19]

Shaker table testing takes a comprehensive approach to evaluating the entire suspension system. Engineers can observe how different components interact under dynamic conditions by placing a fully assembled vehicle on the shaker table. This provides valuable insights into the overall behavior of the suspension system, ensuring that all suspension parts work together seamlessly for optimal performance.

While shaker table testing offers numerous advantages, it's crucial to acknowledge its limitations. It's not a perfect substitute for real-world testing, as the controlled conditions of a shaker table cannot fully replicate the complexities of real-world driving. Temperature, weather, and driver behavior can significantly affect suspension performance. However, shaker table testing remains a valuable tool for suspension development, providing a controlled environment for evaluating and optimizing suspension components and systems.

2.5.3 Road Load Data Acquisition (RLDA)

Road Load Data Acquisition (RLDA) is a technique that collects real-world data on how a vehicle's suspension system responds to actual road conditions. This involves outfitting a car with various sensors and data acquisition systems, such as accelerometers, strain gauges, and displacement sensors. These instruments measure forces, vibrations, and movements as the vehicle is driven over different terrains, providing a comprehensive understanding of the suspension system's real-world performance.

One of RLDA's main advantages is its ability to capture real-world data that reflects the actual conditions a vehicle will encounter during its operational life. Unlike laboratory tests conducted in controlled environments, RLDA provides insights into how the suspension system behaves under various conditions, including road surfaces, speeds, and weather. Data is typically collected over a series of test drives that cover a variety of road types, such as smooth highways, rough gravel roads, and urban streets with potholes and speed bumps. By analyzing the data from these drives, we can identify patterns in how the suspension responds to different inputs and use this information to optimize the design and tuning of the system.[20]

Another critical aspect of RLDA is its ability to capture transient events, such as sudden bumps or sharp turns, which can significantly impact suspension performance. By analyzing how the suspension system responds to these events, engineers can assess its ability to maintain vehicle stability and control, which is crucial for safety and handling. This information is also valuable for tuning active suspension systems, which can adjust their real-time settings to respond to changing conditions.

In addition to its use in suspension development, RLDA is also a valuable tool for validating vehicle models and simulations. By comparing real-world data with predicted results from computer models, engineers can assess the accuracy of their simulations and make necessary adjustments. This is especially important for developing suspension systems that perform well across various conditions, from smooth highways to rugged off-road trails.[21]

2.6 Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a computational method to predict how a suspension system will behave under different loads and conditions. In FEA, the suspension system is modeled in a virtual environment, and complex mathematical equations are used to simulate how the system responds to various forces, such as weight, acceleration, and road vibrations. The advantage of FEA is its ability to provide detailed information about the behavior of suspension components without physical testing. By modeling the suspension system in a virtual environment, engineers can explore various design options and assess their performance under different conditions. This is especially valuable for developing lightweight suspension components, where material strength and fatigue resistance are critical considerations.

FEA is particularly useful for analyzing suspension components' stress and strain distribution and understanding their performance under load. By simulating the effects of different forces, engineers can identify areas of high stress that could lead to material fatigue or failure over time. FEA can be used to evaluate the dynamic behavior of suspension systems. By simulating the system's response to various inputs, such as road vibrations or cornering forces, engineers can assess its ability to maintain vehicle stability and control. It also allows for optimizing suspension designs by enabling engineers to explore different materials, geometries, and configurations. By simulating these variables' effects, engineers can identify the most effective design solutions for achieving the desired balance between comfort, handling, and durability. This is particularly valuable in the early stages of development, where design changes can be made quickly and cost-effectively.[22]

While FEA offers many advantages, it is essential to note that there are better substitutes for real-world testing. The accuracy of FEA predictions depends on the quality of the input data and the assumptions made during the modeling process. FEA is often used with physical testing methods, such as accelerometer measurements and strain gauge testing, to validate the results and ensure that the suspension system performs as expected in the real world.

By combining FEA with other testing methods, engineers can develop suspension systems that are both highly performing and reliable, meeting the needs of drivers and passengers in a wide range of conditions.

Finite Element Analysis serves as a powerful tool for evaluating suspension system behavior under various operating conditions, offering detailed insights into stress distribution, material performance, and dynamic response. However, while FEA enhances the design and development process, its accuracy remains dependent on the quality of input data and modeling assumptions. Therefore, combining FEA with real-world testing, such as accelerometer measurements and strain gauge analysis, is essential to validate results and ensure that suspension systems meet performance expectations in practical applications.

2.7 Previous studies and simulations

Lithium batteries have become OEMs' most used battery composition due to their high energy storage capability and recharging capacity. This technology comes with some challenges, such as its sensitivity to external variations like temperature, pressure, and, for this thesis, vibration. Controlling external variations is crucial to obtaining maximum battery capacity and life expectancy.

Research conducted by Hooper et al. and Zhang et al. [1] has significantly advanced our understanding of material degradation in batteries subjected to vibrational stress and its impact on performance. These studies examined the deterioration of both mechanical and electrical properties of battery cells subjected to excessive vibrations. Using advanced statistical methodologies, they could predict battery life expectancy and performance decline post-exposure to vibrations.

Innovative methodologies were introduced to predict and analyze the structural dynamics of battery packs and cells under vibrational stress. These included using Parametric Reduced-Order Models (PROMs) and single-axis acceleration tests as cost-effective alternatives to more intricate methods. These advancements offer promising results for enhancing the design and testing of lithium-ion batteries, thereby ensuring their reliability and safety in applications where vibrations and shocks are prevalent.

Expanding their research, Hooper et al. Zhang employed a six-degree-of-freedom simultaneous testing approach to study the effect of vibrations on cell durability, providing a more accurate representation of the vibrations experienced by electric vehicle batteries. The study revealed that their direct current resistance increases significantly when cells undergo vibrations that are representative of a decade-long vehicle lifespan. However, the overall electromechanical performance does not exhibit notable degradation. [1].

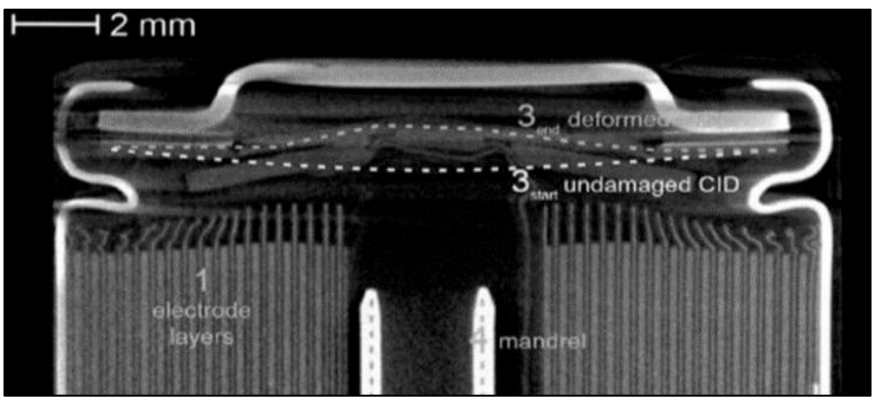

Figure 3. Adapted from "Effect of dynamic loads and vibrations on lithium-ion batteries" Deformed cylindrical cell after 300 shocks in Z direction . Journal of Low Frequency Noise, Vibration and Active Control [23]

The study by Eager et al [2] examines seat vibrations in city buses using a 6-axis inertial measurement unit (IMU) to measure accelerations in the longitudinal, lateral, and vertical directions. Their analysis reveals that vertical accelerations are the dominant factor contributing to passenger discomfort, with peak values reaching up to 0.44 g during significant speed changes, such as starts and stops, as well as when traversing road irregularities. The researchers highlight that median vertical accelerations during regular cruising were around 0.12 g, with higher acceleration levels closely linked to jerk, which is suggested as a better indicator of discomfort than acceleration alone.

The research emphasizes how the dynamics of vehicle motion, particularly the abruptness of acceleration and deceleration, impact passenger experience, something that is critical to understanding the human response to vibrations in various transport contexts.

The methods employed by Eager et al. [2], including the application of algorithmic filters and acceleration peak detection, provide a framework for characterizing vibration profiles in real-world scenarios. While their study focuses primarily on urban buses and passenger comfort, the methodologies and insights are highly relevant to my research, particularly in the context of heavy-duty electric trucks. The article discusses potential mitigation strategies, such as designing advanced materials and ergonomic seating solutions to reduce vibration transmission. My research complements these ideas by exploring how optimized vibration modeling can inform the design of suspension systems and vehicle components for electric trucks.

By comparing the field data from different test environments, such as real roads and dedicated test tracks, and replicating these conditions in the laboratory, my approach ensures a comprehensive understanding of vibration dynamics and their implications. This comparison will serve as a key step in establishing a standardized methodology for vibration modeling in electric heavy-duty trucks, one that can be applied to various manufacturers and models to optimize their performance in terms of comfort, durability, and energy efficiency.

A distinctive aspect of this thesis is the integration of real-world field data into a repeatable laboratory environment, enabling the development of accurate and scalable models for the electric truck sector. The variability of road conditions and drivers' behavior presents a significant challenge in vehicle dynamics modeling. This research addresses this issue by synthesizing real-world data with controlled simulations, ensuring a more representative analysis of operational conditions. By doing so, the study provides valuable insights into the effects of different vibration frequencies and magnitudes on vehicle components, particularly the impact of sustained vibration exposure on the performance of battery systems.

Chapter 3: Methodology

3.1 Introduction

This chapter presents the research design adopted to evaluate the impact of vibrational stress on lithium-ion battery performance in heavy-duty electric trucks. Given the highly variable conditions these vehicles experience, this study integrates experimental and applied methodologies to develop an understanding of battery durability. By using field data collection, the research ensures that findings are both empirically grounded and practically applicable.

The fundamental objective of this study is to bridge the gap between standardized vibration testing protocols and real-world operating conditions. Existing regulatory standards, while essential for safety and compliance, often rely on simplified sinusoidal waveforms that do not fully capture the complex vibrational stresses imposed on electric heavy-duty vehicles. To address this limitation, the study leverages real-world vibrational profiles collected from electric heavy-duty trucks operating on dedicated test tracks and actual road conditions. This data set provides a more accurate representation of the forces affecting battery systems in daily operations.

Ensuring the precision and reproducibility of the research is another key consideration in the study design. High-accuracy accelerometers and advanced signal processing tools are employed to minimize errors and standardize the vibrational data collected. Additionally, data cleaning and compilation techniques are applied to remove noise and inconsistencies, ensuring the extracted information remains representative of real-world conditions. The Power Spectral Density (PSD) method is then used to quantify vibration characteristics, allowing for a more detailed analysis of frequency-dependent stress factors affecting the battery system.[24]

By establishing a structured research framework, this chapter lays the groundwork for subsequent experimental investigations. The methodologies outlined are designed to deliver a robust analysis of battery resilience, contributing to the ongoing optimization of battery durability and performance in electric heavy-duty transportation. Through this approach, the study provides valuable insights for improving battery design, enhancing operational efficiency, and ensuring the long-term sustainability of electrified heavy-duty vehicles. Furthermore, by incorporating real-world vibration envelopes into laboratory testing procedures, the research aims to offer a more practical perspective on battery degradation mechanisms, facilitating better engineering solutions for future EV applications.

3.2 Research Design

The research process starts with field data collection, where vibrational data were recorded from electric heavy-duty trucks operating on a designated test track and actual road conditions. High-precision accelerometers were strategically mounted on critical vehicle components, particularly the battery pack, chassis, and suspension system, to capture real-world vibrational inputs. These sensors continuously logged acceleration data across various driving scenarios, including uneven terrain, speed bumps, aggressive turns, continuous acceleration, stop-and-go traffic, and inclines. The field tests aimed to provide an accurate representation of the dynamic forces affecting the vehicle and its battery system under different operational conditions.

Once the raw field data was collected, it went through a cleaning and compilation process to remove noise, inconsistencies, and irrelevant signals. Advanced filtering techniques were applied to eliminate extraneous vibrations caused by external factors such as sensor interference or environmental disturbances. The refined dataset was then used to generate Power Spectral Density (PSD) plots, which are essential for understanding the distribution of vibrational energy across different frequencies. By analyzing multiple test iterations, the PSD results were combined to produce a single envelope representing the overall vibrational profile experienced by the vehicle. This step ensured that the research captured a comprehensive and statistically significant vibrational signature.

While the research successfully captured and processed the vibrational data, the replication of field test conditions in a controlled laboratory environment was not completed due to time and resource constraints. The developed PSD envelope provides a reliable framework for future experimental validation, where a vibration test rig can be programmed to reproduce the recorded vibrational stresses. This step, planned for further investigation, would allow direct comparisons between real-world data and controlled simulations, enhancing the accuracy of predictive models. Despite this limitation, the research offers valuable insights into the vibrational characteristics affecting battery performance and establishes a solid foundation for continued advancements in heavy-duty electric vehicle testing methodologies. This process is illustrated in Figure 4.

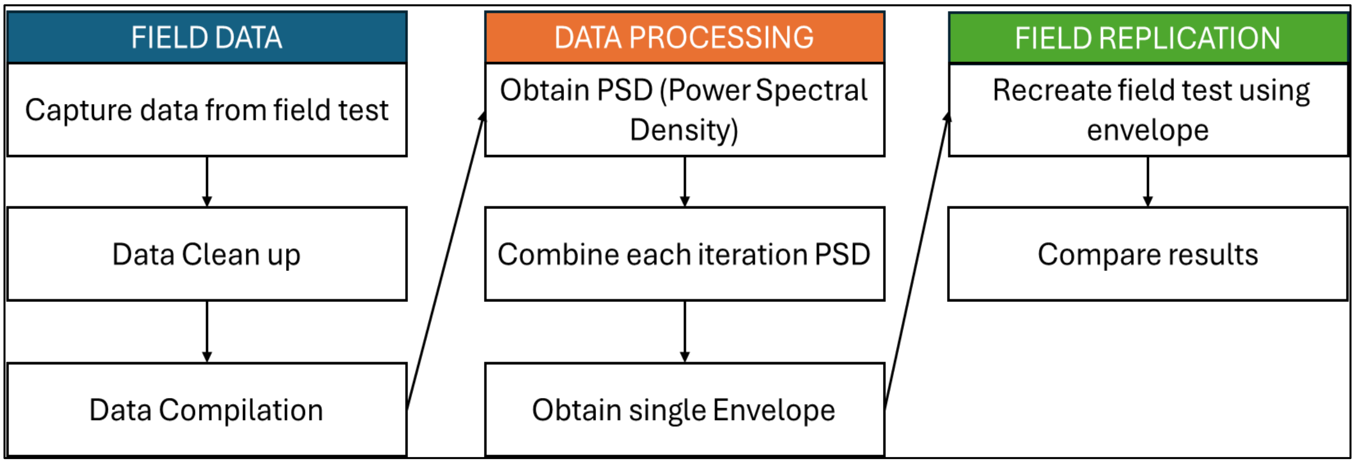

Figure 4. Process diagram for envelope calculation.

3.3 Experimental Framework

3.3.1 Design of Test Track

Designing the test will require using an existing test track at Navistar facilities at Escobedo, Nuevo Leon. Also, some areas will be on roads with the necessary conditions near the plant facilities. The test track will simulate various real-world conditions that electric heavy-duty trucks experience, creating a controlled environment to induce different vibrations. The following sections outline the critical areas of the track, along with their objectives, distances, speed, and repetitions to ensure comprehensive data collection:

Uneven Terrain

Objective: Simulate off-road conditions or poorly paved areas that the truck might encounter in non-motorway zones. This road is illustrated in Figure 5.

Distance: 500 meters.

Velocity: 20-30 km/h to recreate the conditions typically experienced in these environments.

Iterations: 5 runs. This ensures a consistent understanding of how repeated exposure to rough surfaces affects the vehicle's battery and structural integrity.

Figure 5. Uneven terrain zone. Provided by Google Earth.

Speed Bump Zone

Objective: Replicate urban environments where speed bumps occur every day. This section is crucial to assess how slowing down and passing over bumps affect the stability of the battery system.

Distance: 200 meters, with four evenly spaced bumps.

Velocity: 10-15 km/h. Iterations: 10 runs. Multiple passes are necessary to understand how repetitive impact affects the system's stability and durability. This road is illustrated in Figure 6.

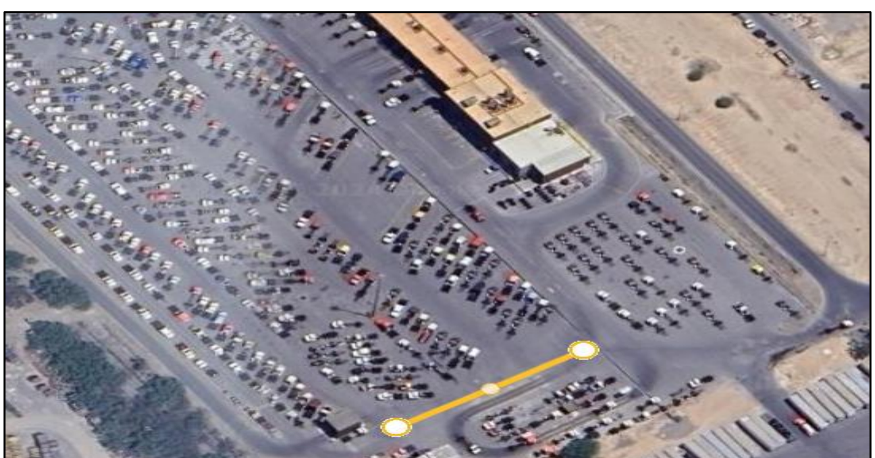

Figure 6. Speed bump zone. Provided by Google Earth.

Aggressive Turns

Objective: Test the vehicle's response to sharp lateral vibrations caused by turning. Two areas will be selected, one for left-hand turns and one for right-hand turns. This road is illustrated in Figure 7.

Distance: 100 meters for each turn.

Velocity: 30-40 km/h to mimic a realistic turning scenario on sharp curves.

Iterations: 8 runs for both left and right turns to fully evaluate the lateral impact on the vehicle and the battery.

Figure 7. Aggressive Turns Circuit. Provided by Google Earth.

Continuous Acceleration

Objective: Simulate a motorway journey with moderate, steady speed, assessing how prolonged continuous driving impacts the battery and overall structure.This road is illustrated in Figure 8.

Distance: 1 kilometer.

Velocity: 70-80 km/h to simulate motorway conditions.

Iterations: 4 runs. This will provide sufficient data on the effects of sustained acceleration.

Figure 8. Constant Acceleration zone. Provided by Google Earth.

Stop-and-Go Traffic Simulation

Objective: Recreate frequent braking and acceleration conditions typically encountered in urban traffic. This is essential for understanding how frequent speed changes influence battery performance and vehicle stability.This road is illustrated in Figure 9.

Distance: 500 meters with frequent stopping points.

Velocity: 0-30 km/h.

Iterations: 8 runs are required to account for the variability in braking and acceleration patterns and ensure a broad dataset.

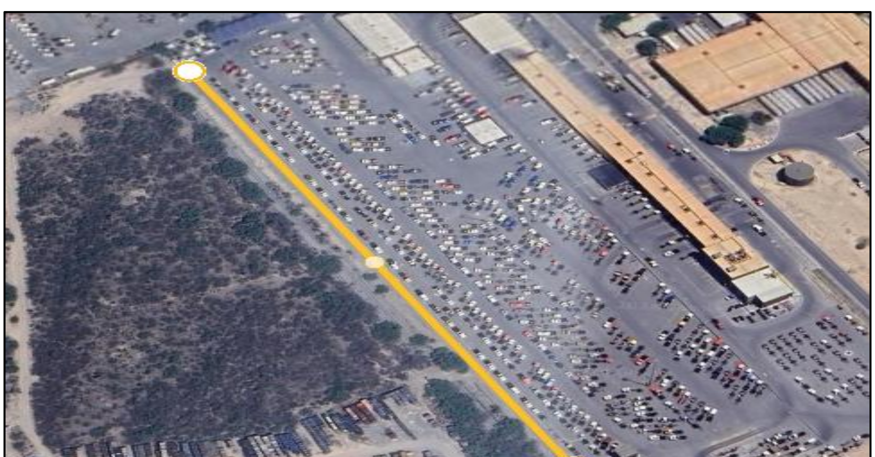

Figure 9. Stop and Go zone. Provided by Google Earth.

Inclines and Declines

Objective: Simulate hill driving by subjecting the truck to an incline and then a descent. This section is essential to measure how slopes affect the vibration profile of the vehicle. This road is illustrated in Figure 10.

Distance: 300 meters with a 15-degree incline.

Velocity: 20-40 km/h, depending on the grade.

Iterations: 4-6 runs, alternating between uphill and downhill to ensure the effects of both are fully captured.

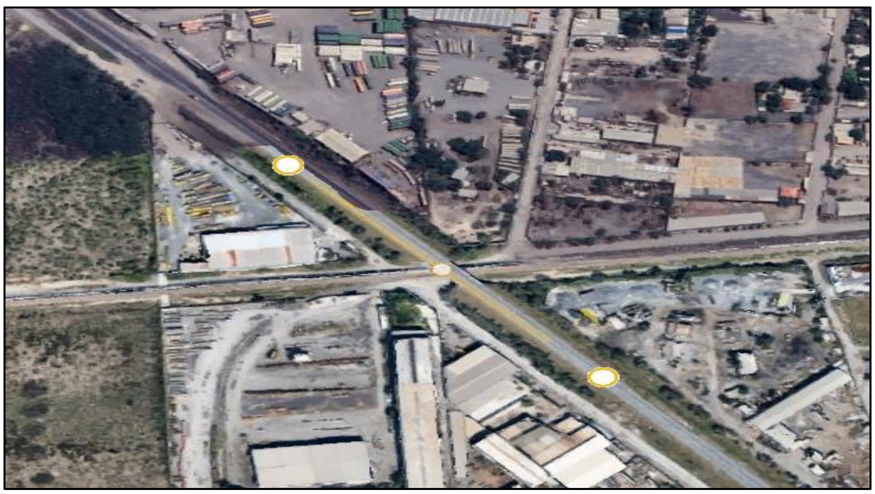

Figure 10. Incline and Decline zone. Provided by Google Earth

3.4 Vehicle Description

For this study, the electric vehicle under analysis is the International eMV Series electric commercial truck. This model stands out as a revolutionary advancement in electric heavy-duty trucks, offering a blend of practicality, adaptability, and dependability. Its electric powertrain is built upon the well-established chassis of the diesel-powered International MV Series, providing a robust and familiar platform optimized for zero-emission operations.

Key features of the International eMV include a typical range of 217 kilometers, which varies based on environmental factors, driving patterns, load weight, and the utilization of its regenerative braking system. The truck is powered by a 210 kWh Lithium Iron Phosphate (LFP) battery pack, a critical component for this study, as its performance under vibration is a central focus. This battery supports peak power output equivalent to 342 hp. It operates at a nominal voltage of 609 V. A thermal management system maintains the battery's operating temperature using standard red coolant, and the truck offers three levels of regenerative braking, contributing to energy efficiency during operations.

The truck's Gross Vehicle Weight Rating (GVWR) ranges from 11,793 kg to 14,969 kg. The front axle, a Dana Spicer I-Beam, has a load capacity of 5,443 kg, while the rear single axle supports up to 10,433 kg. The rear suspension utilizes an IROS air suspension system, which enhances ride comfort and load distribution. These components are vital in understanding how the vehicle manages the forces and vibrations encountered during operation, making them relevant to the study.[25]

Figure 11. IROS suspension system.

3.5 Focused Components

Battery Pack: This study focuses on the truck's high-voltage 210 kWh Lithium Iron Phosphate battery system. This battery is critical for propulsion and understanding how vibrations affect its longevity, efficiency, and thermal management. The study will investigate how this system performs under real-world vibrational loads, including the impact of uneven terrain and sustained motorway driving.

Chassis Sections: The truck's frame is constructed from heat-treated alloy steel with a strength of 827 MPa, designed to withstand heavy loads and external forces. The study will examine how the chassis manages vibrations transmitted from the axles and road surface. The parabolic taper leaf front suspension and IROS air rear suspension will be crucial in understanding the truck's capacity to absorb and dissipate vibrations.

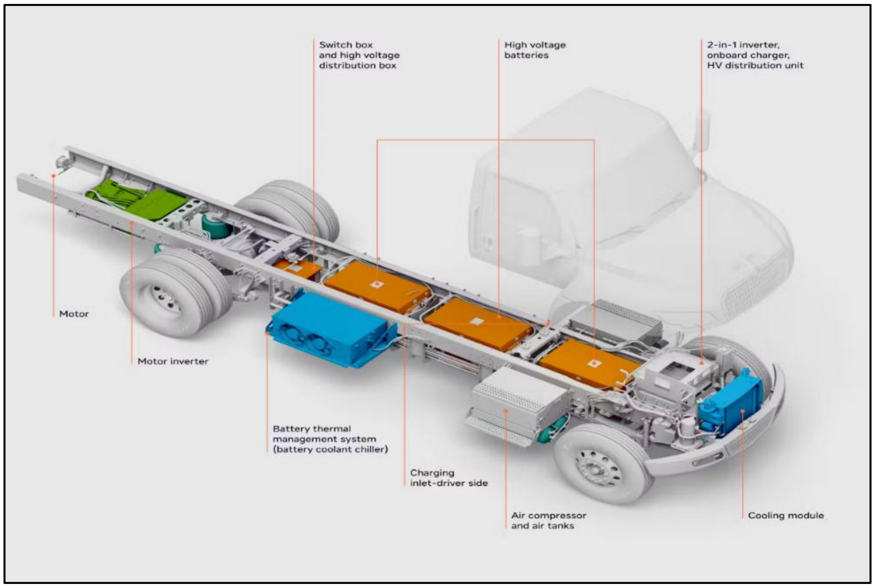

Figure 12. MV schematics. Image from International sales page

Axle and Suspension System: The Dana Spicer axles and the truck's advanced suspension systems are vital in transmitting and moderating vibrations from the road to the chassis and battery pack. By focusing on the interplay between these mechanical systems, the study aims to provide insight into their efficiency in maintaining vehicle stability and protecting the battery pack from excessive vibrational stress.

Brakes and Steering: The truck has air brakes incorporating ABS and an electronic stability program with traction control. These systems will also influence performance under varied vibrational

Figure 13. e MV Model. Provided by International sales page

conditions, ensuring that stopping power and steering stability are not compromised during operation on different surfaces.

3.6 Environmental variables measured

One of the primary variables under investigation is vibration frequency, which plays a role in determining the stresses that battery components endure over their operational lifespan. Frequency refers to the number of oscillations per second experienced by the battery, often measured in hertz (Hz). In electric heavy-duty trucks, these frequencies can vary widely based on road conditions, truck velocity, and cargo load. High-frequency vibrations, normally generated by rough road surfaces or operational components such as engines or electric drive systems, are particularly important. These vibrations can penetrate deeply into the battery's microstructure, causing fatigue in materials and leading to cumulative damage. Measuring, classifying, and analyzing these frequencies is fundamental to the project's goal of developing accurate and predictive vibration profiles.

Another critical variable is vibration amplitude, which quantifies the magnitude of the vibrational forces acting on a system. Amplitude directly correlates with the intensity of the vibrations, determining the extent of physical deformation or stress induced in components. Larger amplitudes are especially concerning as they can result in severe mechanical impacts, such as the loosening of cell connections. These effects compromise the battery's structural integrity and reduce its ability to store and discharge energy efficiently. Capturing the full spectrum of amplitudes encountered during typical vehicle operation is key to assessing the robustness of battery cells and packs when exposed to real-world vibrational stresses.

The interaction between frequency and amplitude creates a complex vibrational environment that directly impacts battery performance and durability. High-frequency, low-amplitude vibrations may not appear immediately destructive but can cause long-term microstructural fatigue. On the other hand, low-frequency, high-amplitude vibrations can lead to severe mechanical failures, particularly in poorly mounted or designed battery packs. Understanding how these variables interact in dynamic operating conditions allows for a more complete evaluation of battery resilience, forming the basis for predictive models and testing standards. [26]

3.7 Data collection and processing methods

3.7.1 Accelerometers

For this thesis, accelerometers from the brand enDAQ were used, specifically the model W8-D40. The W8-D40 Vibration Sensor from enDAQ is a suitable instrument for this thesis due to its ability to precisely capture vibration data across a wide frequency range. Its dual accelerometer system—combining piezoelectric and capacitive sensors—enables comprehensive monitoring of vibration frequencies and amplitudes.

The piezoelectric accelerometer features a sampling rate of up to 20,000 Hz and a dynamic range of ±25g, making it particularly well-suited for detecting high-frequency vibrations. In contrast, the capacitive accelerometer, with a broader range of ±40g and a sampling capacity of up to 4,000 Hz, facilitates the measurement of low-frequency vibrations. These features ensure a thorough representation of the vibrational environment batteries are exposed to, aligning directly with the project's objectives.

Figure 14. enDAQ W8-D40 sensor

The sensor's durability and adaptability justify its selection for this study. Constructed with robust materials such as aluminum and polycarbonate, the W8-D40 is capable of withstanding extreme shocks and operating across a wide temperature range (-40°C to 80°C). These characteristics ensure its reliability in field testing. Moreover, its standalone functionality, which includes a rechargeable battery and internal data storage, allows for long-duration data collection without the need for constant monitoring. This is particularly beneficial for capturing extended vibration profiles. In terms of implementation, the sensor's simple mounting options, whether through screws or industrial adhesive, facilitate secure placement on the truck chassis. This ensures accurate data collection by minimizing measurement errors caused by poor adhesion or misalignment. Additionally, the device's compatibility with enDAQ's analysis software simplifies the processing of large datasets, enabling efficient extraction and interpretation of key vibration characteristics. The ability to generate detailed visualizations further supports the analytical depth required for this research. Furthermore, this

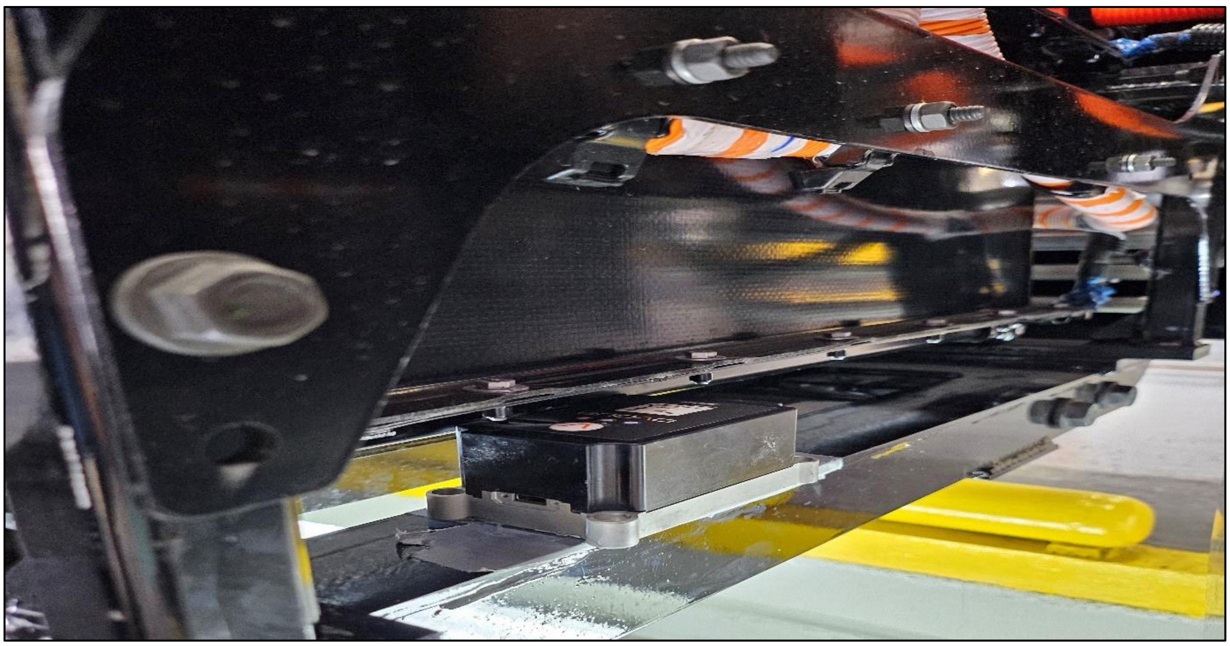

Figure 15. Sensor mounted using adhesive under battery crossmember

device's technical specifications, including detailed descriptions of its accelerometer configuration, sampling rates, operational thresholds, and environmental sensors, are included in Appendix 1.

The W8-D40 Vibration Sensor from enDAQ is calibrated at the factory to ensure precise and reliable performance across its operational range. This calibration process involves testing of its dual accelerometers (piezoelectric and capacitive) to confirm accuracy in measuring vibration frequencies and amplitudes. Calibration standards are aligned with industry norms to ensure consistency and repeatability of measurements, particularly for critical ranges relevant to automotive and industrial applications. Additional information on the W8-D40 Vibration Sensor is listed in its data sheet in Appendix 1.

3.7.2 Software: enDAQ

The enDAQ software was important for processing and visualizing the vibration data collected during the tests. This tool facilitated the analysis of vibration frequencies across the X, Y, and Z axes,

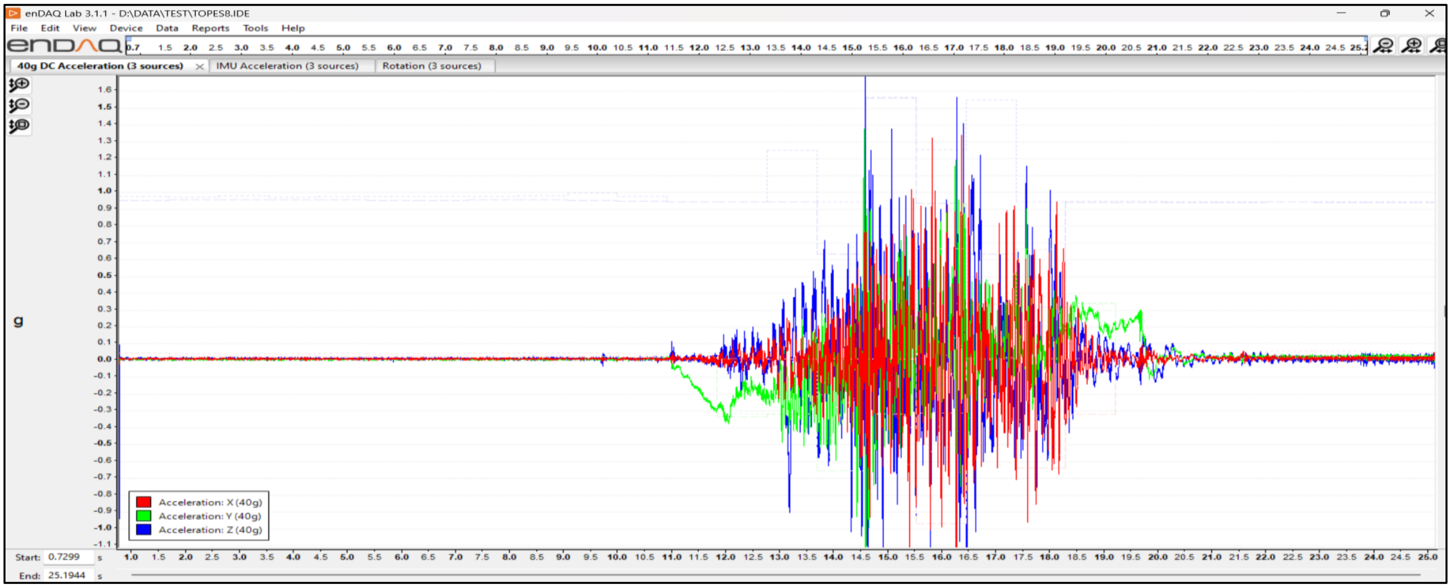

Figure 16. Test 8 Bumper Zone

offering detailed insight into the multidirectional forces acting on the battery system. By using its visualization features, the software enabled a clear representation of frequency distributions and amplitudes, allowing the identification of patterns and irregularities in the vibrational behavior. This visualization proved essential for understanding the specific stresses batteries encounter under operational conditions.

One key application of the enDAQ software in this research was its ability to crop zones of interest within the vibration datasets. Segments of data captured when the truck was stationary or awaiting instructions were manually excluded to ensure the analysis focused solely on active vehicle movement. This filtering process improved the accuracy of the vibration profiles by removing noise and irrelevant data, thereby enhancing the reliability of subsequent analysis. The software's interface and data processing capabilities improved this task, making it easier to handle large datasets.

Additionally, the enDAQ software was used to compute the Power Spectral Density (PSD) of the Z-axis vibration data. The PSD represents the distribution of power into frequency components, effectively quantifying the intensity of vibrations across the frequency spectrum. By focusing on the Z-axis, often the most critical for vertical vibrations affecting the battery pack, the PSD analysis provided a comprehensive understanding of the vibrational energy experienced by the system. This information was vital for identifying high-energy frequency ranges that contribute most significantly to potential battery degradation.

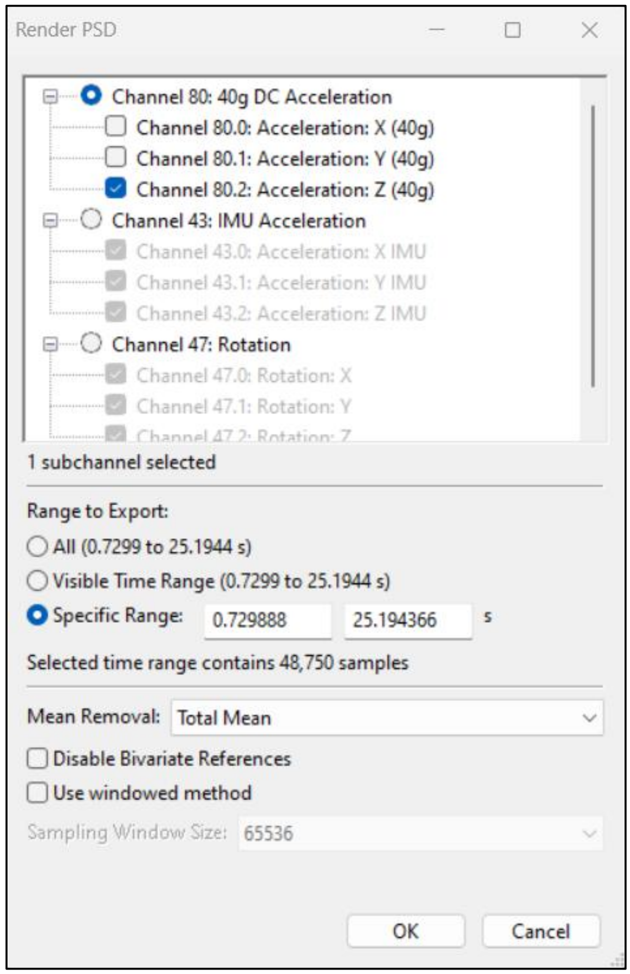

Figure 17. PSD Render Menu

3.7.3 Software: MATLAB

In addition to the enDAQ software, MATLAB software played an important role in the analysis and visualization of vibration data for this thesis. The Vibration data MATLAB Signal Analysis & Structural Dynamics Package, developed by engineer Tom Irvine and the MATLAB community, was particularly useful for processing the data and generating comprehensive spectral analysis. This software package allowed for the visualization of Power Spectral Density (PSD) for each test sample, enabling a clear representation of the frequency distribution of vibrational forces. The research and additional applications developed by Engineer Tom Irvine, which were used in this analysis, are included in the appendix of this thesis for reference.

Using simple MATLAB commands, all the individual PSDs from the various test samples were aggregated and plotted on a single graph. This allowed for a view of the overall vibrational characteristics across all the samples of a particular condition tested. The ability to visualize multiple PSDs in one unified graph made it easier to identify common patterns and deviations between tests.

For this example, the 4 iterations in acceleration and brake were plotted into a single PSD diagram:

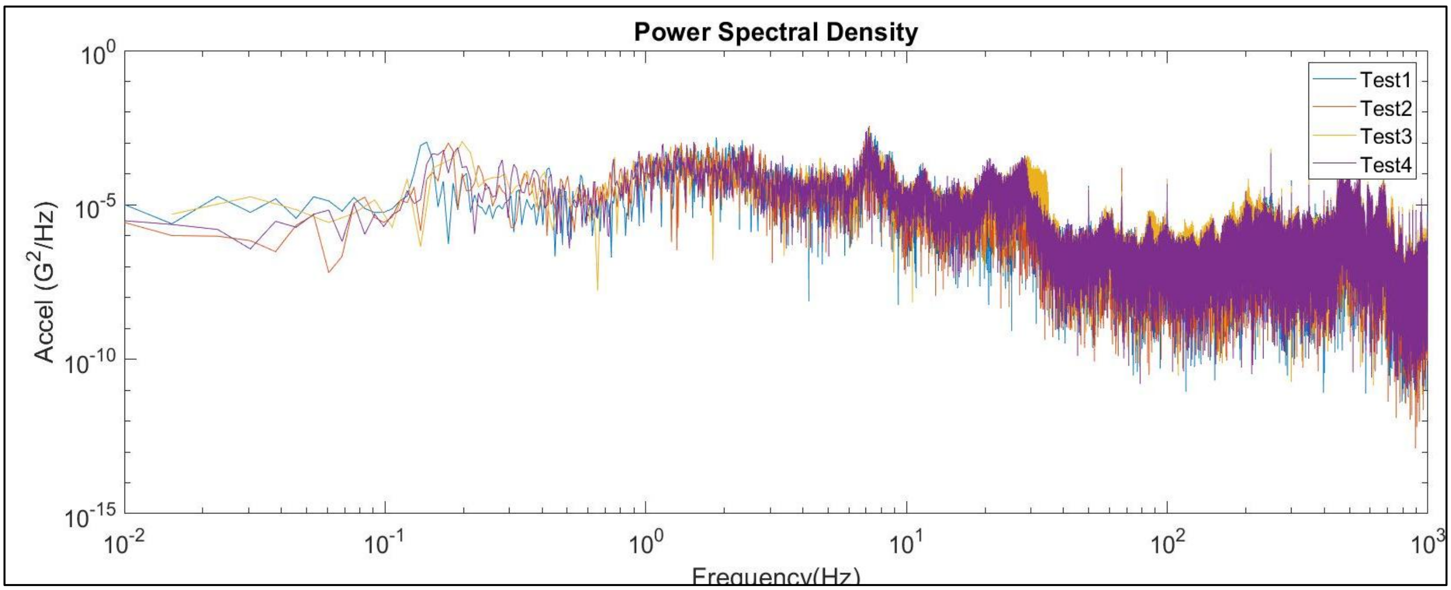

Figure 18. PSD diagram with all acc. and brake iterations

This visualization helped to validate whether the test information and PSD were properly done. The same patterns were observed, and frequency ranges were similar in all iterations. The next step is to create a single envelope that can accurately represent the data shown in these iterations

To ensure the robustness of our vibration analysis, we developed a method for combining multiple power spectral density (PSD) datasets into a single matrix. This combined matrix was structured to align acceleration data from different field tests to a common frequency vector. The approach involved defining a unified frequency range and interpolating acceleration values from each dataset to match this range. Then append the interpolated values into a single matrix. By consolidating the data this way, we ensured consistency across datasets, enabling a more reliable and comprehensive analysis of vibration profiles.

The variability in field test data drove the decision to create a combined matrix. Each test, while capturing important PSD characteristics, could have slight differences in frequency resolution or range due to variations in measurement equipment or testing conditions. Without alignment, comparing these data sets would be challenging, potentially leading to inaccuracies in subsequent analysis. By interpolating the acceleration values to a shared frequency vector, we eliminated inconsistencies and standardized the datasets, ensuring that each test was given equal weight in the analysis.

The resulting combined matrix featured a column of common frequencies and multiple columns of interpolated acceleration data, one for each test. This structure was crucial for further processing, as it allowed the calculation of an envelope that represented the worst-case vibration scenario across all tests. The matrix effectively became the input for a script designed to compute a PSD envelope using statistical methods. This matrix-based approach ensured that the analysis was not limited to individual datasets but rather captured the variability and extremes observed across all tests.

For the envelope calculation, a custom script was employed to process the combined matrix. This script utilized a normal tolerance factor approach, assuming a normal distribution for the data. With a 90% probability and a 90% confidence level, the script calculated an optimized PSD envelope that enveloped the acceleration values across all tests. This statistical approach ensured that the envelope was conservative and realistic, representing the upper bound of vibration levels that could be expected across the range of test conditions. The script's reliance on probabilistic parameters added rigor to the analysis, accounting for both expected variations and outliers within the data.

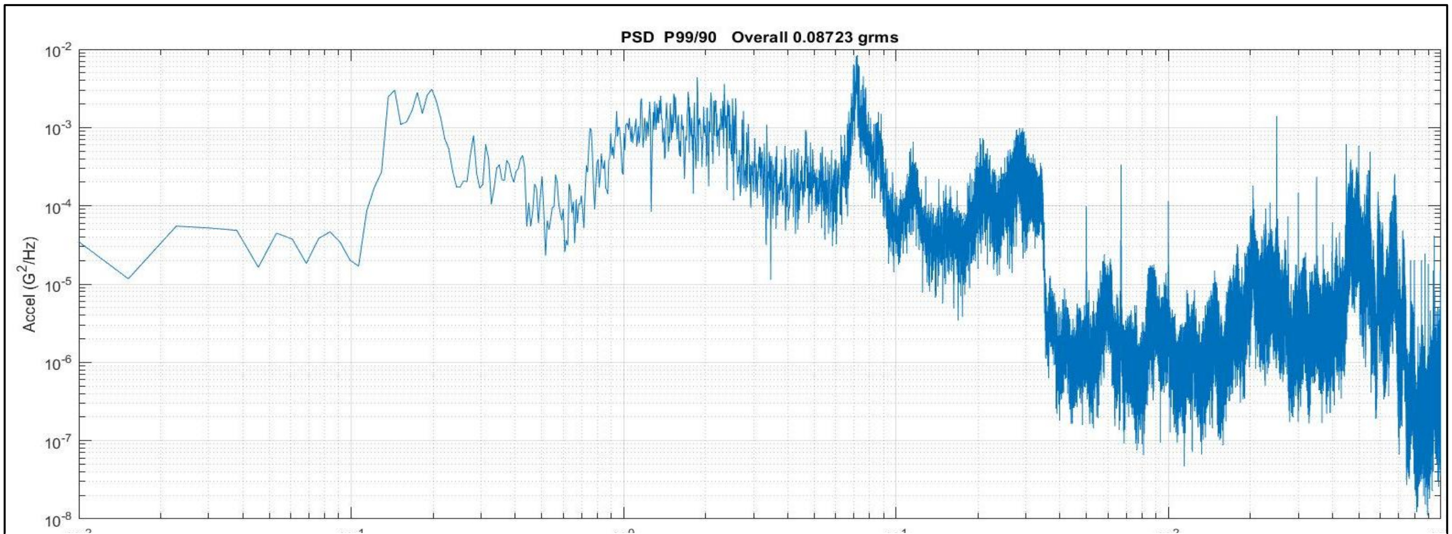

Figure 19. Combined Matrix of Acceleration and Brake testttttttc

The matrix provided a comprehensive view of all test data, enabling the envelope to reflect the collective behavior of the vibration profiles rather than focusing on a single dataset. This ensured that the derived PSD envelope was representative of the test environment and robust enough to serve as a reliable input for laboratory replication. By adopting this methodology, we established a standardized framework for processing multiple PSD datasets and generating an envelope that accurately captures the dynamics of field test conditions.

By applying this technique, the thesis achieved the crucial objective of standardizing the vibrational data collected from field tests. This envelope represents the average vibrational

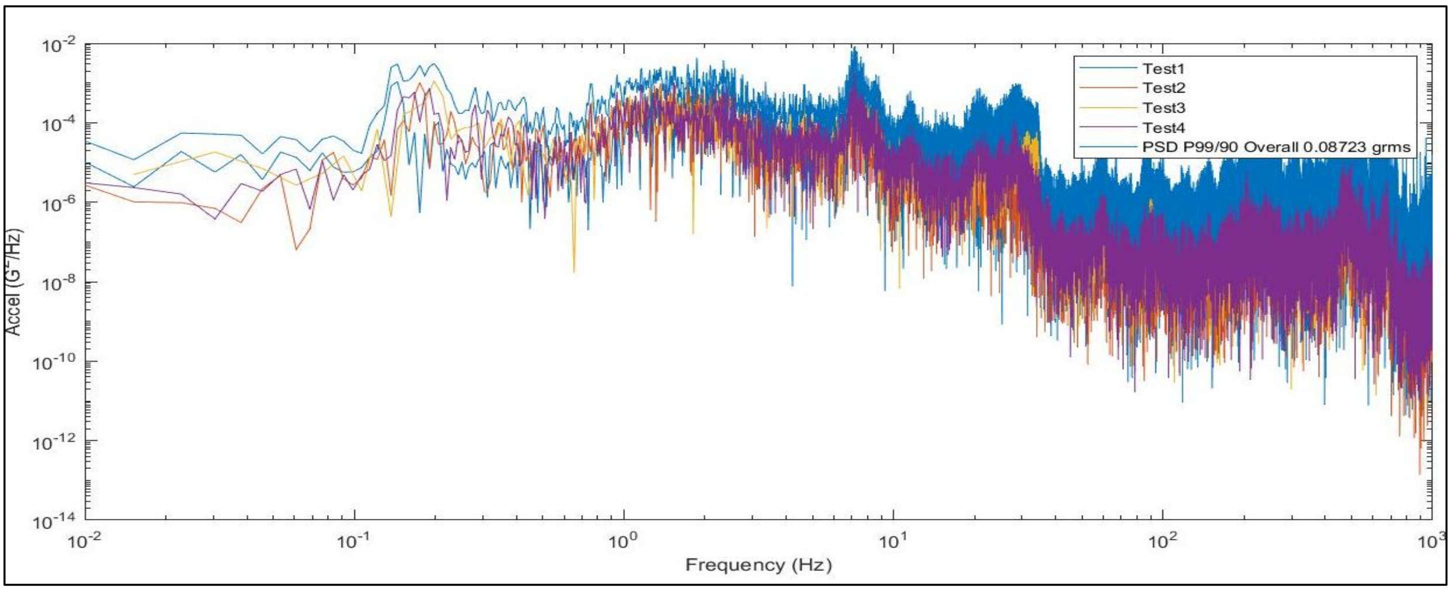

Figure 20. Combined matrix (blue) and test samples for Acceleration and break test

characteristics under specific operational conditions and can be used to replicate real-world vibrations in controlled lab environments. This standardized envelope will be a foundational model for further studies, ensuring that future battery testing can more accurately simulate actual operational conditions.

Once the representative Power Spectral Density (PSD) profile was defined, encompassing between 90% and 99% of the analyzed cases, the next step involved generating an envelope using the Vibration Response Spectrum (VRS). The VRS describes the peak dynamic response of a set of Single Degree of Freedom (SDOF) systems subjected to the excitation defined by the PSD. Unlike a Shock Response Spectrum (SRS), which characterizes the response to transient impulses, the VRS is computed from a continuous excitation, typically random. This allows for the identification of sustained resonant behavior within the frequency range of interest, which is critical for fatigue analysis and durability testing.

To obtain the VRS envelope, the software performs a high number of virtual simulations, or trials. In each trial, a time-domain signal is synthesized from the PSD using inverse FFT techniques, maintaining both the frequency content and statistical characteristics of the original input. This synthetic signal is then applied to a bank of SDOF oscillators spanning the selected frequency range. For each oscillator, the maximum acceleration response is recorded, and the envelope is constructed by selecting the peak response at each frequency across all trials. In this work, the simulation was configured to process 10,000 trials, which provided a robust statistical foundation for the resulting VRS envelope.

The frequency range selected for the analysis extended from 1 Hz to 10,000 Hz, ensuring that both low-frequency structural responses and high-frequency local resonances were captured. A constant quality factor (Q) was used for all oscillators, representing a standard damping condition commonly applied in automotive vibration qualification tests. From the resulting VRS envelope, critical frequency-response pairs were extracted and later used to define the parameters for fatigue simulation or resonance dwell testing.

In defining the PSD profile used for simulation, various breakpoint configurations were evaluated: arbitrary, ramp–plateau, and ramp–plateau–ramp. These breakpoints determine the shape of the PSD curve, particularly how the energy is distributed across frequency bands. Each configuration was tested iteratively until one was found that not only reflected the dynamic behavior observed in field data but also resulted in a Root Mean Square acceleration (GRMS) value within acceptable limits. The GRMS is a scalar metric representing the overall energy of a random vibration signal, calculated as the square root of the area under the PSD curve. It serves as an essential indicator of the severity of the vibration environment and is often used to ensure comparability between test profiles.

It is important to highlight that the final breakpoint configuration was not only selected based on frequency-domain fitting, but also by considering the resulting GRMS value of the VRS envelope. In this context, maintaining a GRMS value close to that of the original PSD was essential to ensure that the test profile reflected the true vibration severity observed in the field. A significant deviation in GRMS—either higher or lower—would respectively lead to over-testing or undertesting of the system, potentially resulting in unrealistic fatigue predictions. Therefore, several iterations were conducted to adjust breakpoint positions until the envelope profile produced a GRMS value within an acceptable range of the original PSD's GRMS, preserving both energy content and statistical representativeness of the simulated vibration environment.

The resulting envelope can then be superimposed onto the previously constructed combined matrix to visualize the extent of coverage and to verify that the selected profile provides the most accurate possible representation of the observed vibration environment.

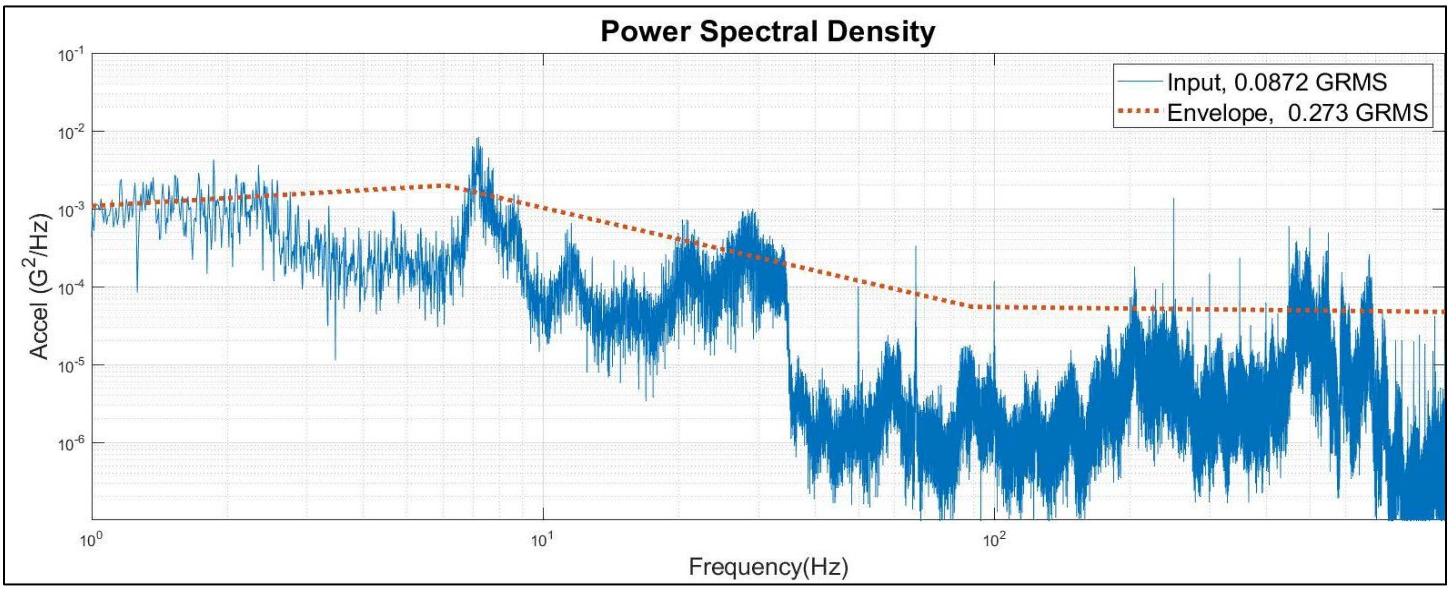

Figure 21. Combined Matrix and Envelope for Acceleration and brake test

This graphical comparison serves as a key validation step in confirming the adequacy of the envelope for simulation or testing purposes. Furthermore, the corresponding envelope data may be tabulated and stored for future reference, either to be utilized in a virtual simulation environment, which constitutes the next phase of this thesis, or for potential application in laboratory-based testing using electrodynamic shakers or similar excitation systems. See Table 1.

Best PSD	
Freq(Hz)	Accel(G^2/Hz)
1	0.001083
6.086	0.001988
89.16	5.491e-05
996.4	4.727e-05

Table 1. Best PSD table for Acceleration and brake test

In summary, the methodology employed in this study followed a systematic approach to developing a reliable vibration profile for simulation purposes. Initially, real-world testing was designed and executed under controlled conditions on a representative test track, ensuring repeatability and consistency across runs. Careful selection of the accelerometer, mounting orientation, and vehicle zone of interest was essential to obtain accurate and relevant vibration data. Particular attention was paid to ensuring that the sensor installation minimized noise and artefacts, thus enhancing the fidelity of the measurements.

Following data acquisition, the collected signals were processed using MATLAB to compute the Power Spectral Density (PSD) of each test run. A statistical envelope was then generated from the set of PSDs using a tolerance factor ranging between 90% and 99%, yielding a representative profile of the vibration environment. This consolidated PSD was subsequently used as the basis for generating an envelope through a Vibration Response Spectrum (VRS) process. MATLAB routines facilitated the creation of the VRS envelope, trial generation, breakpoint adjustment, and GRMS verification to ensure statistical alignment with the field data. The final envelope was graphically and numerically validated for further use in simulation and potential physical testing.

Chapter 4: Results and Analysis

4.1 Introduction

This chapter outlines the findings from the data collected during on-road testing of a heavy-duty electric vehicle, alongside the steps taken to analyze and interpret those results. The focus lies in understanding the typical vibrational forces acting on lithium-ion battery systems under real operating conditions and in exploring how such data might be applied in future testing environments to improve accuracy and reliability.

During the field trials, a single high-resolution accelerometer was mounted at a carefully chosen location on the vehicle's battery housing. This placement allowed for the capture of meaningful vibrational signals experienced during actual road usage. Once recorded, the data underwent a thorough cleaning process to filter out inconsistencies and eliminate unwanted noise, resulting in a clear and usable dataset that reflected a range of real-world driving scenarios.

From the cleaned dataset, each recorded test run was processed individually to determine its Power Spectral Density (PSD). This step enabled the identification of key frequency bands and energy distribution patterns, offering insight into how vibrations are transmitted through the battery structure. The consistency between individual PSDs was reviewed to assess how repeatable and reliable the vibrational characteristics were across different runs.

The next phase involved combining these individual PSD results into a single statistical envelope. By applying confidence intervals ranging between 90 and 99 percent, a comprehensive profile was developed that captures the vibrational behavior observed throughout all the test sessions. This envelope is intended to serve as a practical reference that can be applied in controlled laboratory environments, offering an improved alternative to the oversimplified waveforms currently used in many testing standards.[27]

While the work presented here successfully demonstrates how field data can be processed into a meaningful form, several limitations remain. For instance, the testing was limited to one vehicle model and one battery type, reflecting the relatively recent development of this technology by the manufacturer. Likewise, only one accelerometer was used in a single position; however, the approach taken in this study is adaptable and can be scaled to incorporate more measurement points and repeated test cycles in future work.

4.2 Limitations

While this study successfully captured and processed real-world vibrational data from electric heavy-duty trucks, several limitations must be acknowledged. The methodology employed enabled the generation of a single envelope that represents, with a confidence level of 90 to 99%, the vibrational stresses experienced across multiple test conditions. However, despite these achievements, there are areas where the research could be further improved to enhance the robustness and applicability of the findings.

One of the primary limitations of this study is the number of iterations conducted during data collection. Although the data set provides a strong representation of the vibrational environment experienced by lithium-ion batteries in real-world conditions, additional test repetitions across a broader range of operating scenarios would have reinforced the statistical reliability of the envelope. More iterations mean better identification of potential outliers or less frequent but impactful vibration patterns that may influence battery degradation over extended periods.

Another constraint during this research was the inability to apply the processed data in laboratory settings or simulation environments. While the study successfully derived a representative vibration profile, resource and time limitations prevented the validation of this envelope through controlled experimental testing. Ideally, a follow-up phase should incorporate laboratory tests using the generated envelope to examine its direct impact on battery performance under controlled conditions.

Furthermore, the integration of this vibrational data into finite element analysis (FEA) models and real-time battery simulations was not within the scope of this thesis. The absence of such simulations means that the study stops short of drawing direct conclusions about the mechanical and electrical degradation mechanisms induced by real-world vibrational stress. However, the methodologies developed here provide a foundation for future studies to incorporate this data into digital models for predictive analysis.

Another limitation is the specificity of the test environment and vehicle conditions. Although the data collected is highly relevant to heavy-duty electric trucks, variations in vehicle load, suspension characteristics, and road surfaces may lead to differences in vibrational impact. Expanding the study to a wider range of vehicle configurations and operational conditions would allow for a more generalized and widely applicable vibration profile for use in testing and validation processes.

Additionally, the study was conducted using a single accelerometer placed at one specific location on the vehicle. While this provided valuable data, it limited the ability to capture a wider vibrational profile of the entire system. However, the methodology developed in this research can be extended to include multiple accelerometers placed at different points on the battery pack and chassis. Incorporating multiple measurement points would allow for a more detailed understanding of how vibrations propagate through the vehicle and how different components respond to mechanical stress. Increasing the number of accelerometers and test iterations would improve the reliability of the generated envelope and improve its applicability in real-world battery testing.

The limitation of a single model of electric heavy-duty truck and a single battery configuration may shorten the data available for the moment. This restriction was due to the novelty of the electric truck models developed by International at the time of the study. As a result, the findings are specific to this vehicle and battery system, limiting the ability to generalize the results across other truck manufacturers or battery technologies. Future studies should seek to validate this methodology on a broader range of electric truck models to ensure its applicability across different platforms.

Despite these limitations, this research contributes significantly to the standardization of how real-world vibrational data can be processed and utilized for laboratory and simulation purposes. The approach presented establishes a precedent for future studies to refine and expand, enabling a more systematic method of translating field data into controlled test conditions. By demonstrating a structured methodology to synthesize real-world vibrations into a representative envelope, this thesis provides a practical framework that can be adopted in both academic and industrial research.

Additionally, while the study was unable to implement real-world vibrational data into laboratory testing, the structured approach developed offers a viable method for future researchers to do so. The envelope generated can serve as a foundation for controlled durability testing and predictive modeling, ensuring that subsequent studies can build upon this work to bridge the gap between real-world data collection and experimental validation.

4.3 Results

4.3.1 Bump test results

1) All iterations

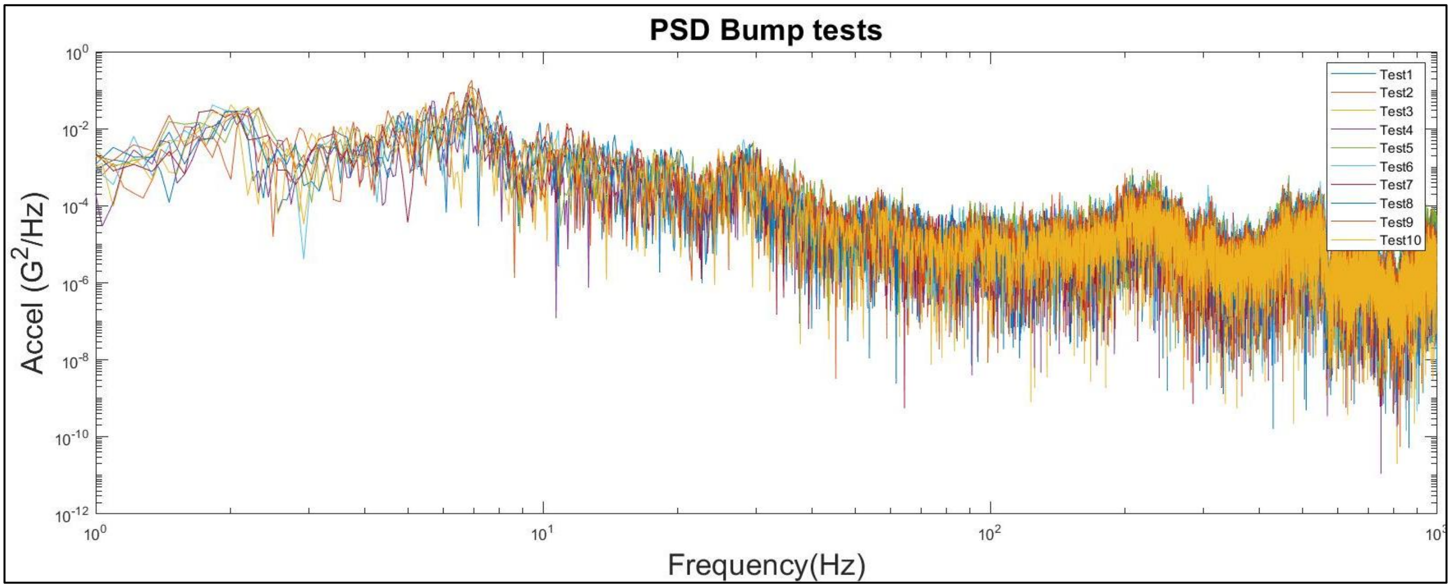

Figure 22: All iterations Bump test

2) Generated Envelope with 99/90% confidence level.

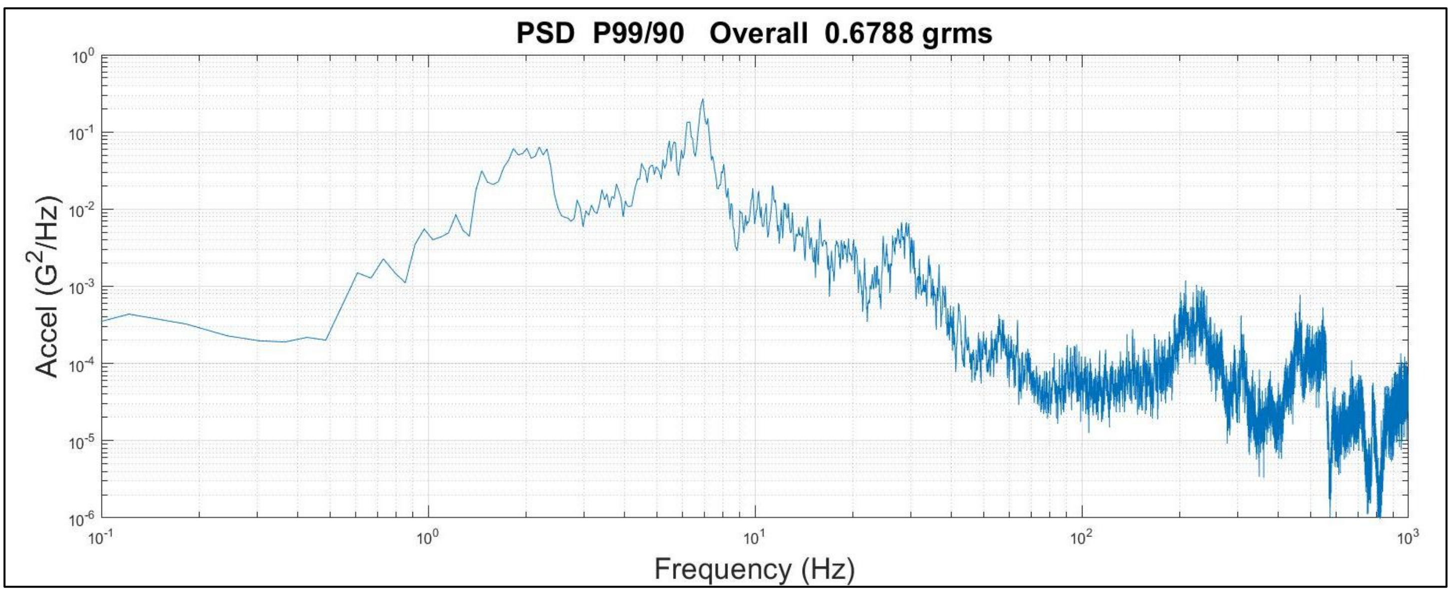

Figure 23. Generated Envelope Bump test

3) Envelope compared to previous PSD:

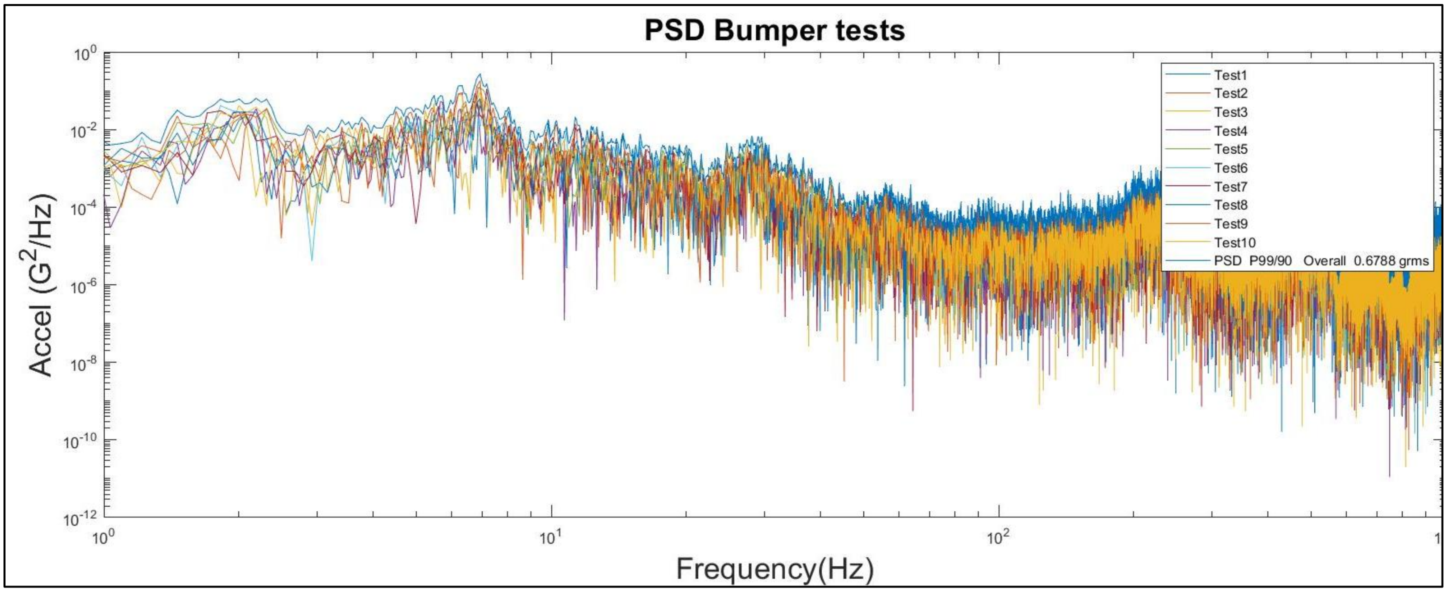

Figure 24. Envelope comparision Bump test

4) Final Envelope and representative 99/90% confidence level

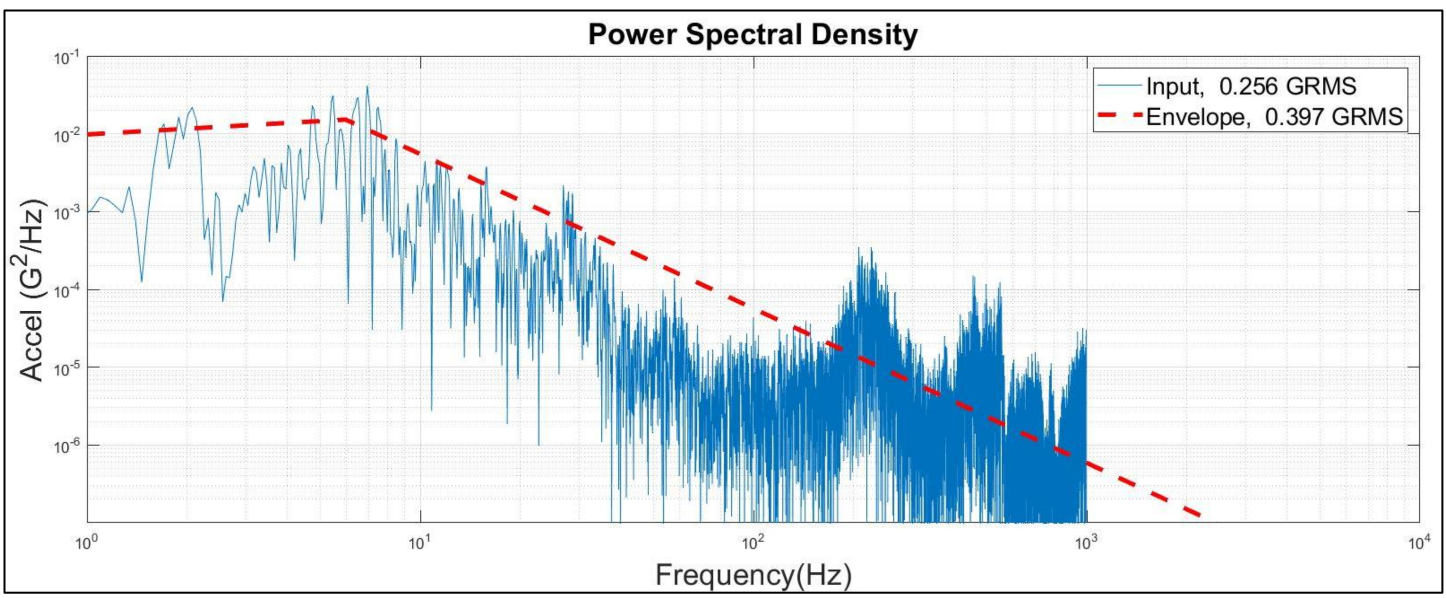

Figure 25. Final Envelope Bump Test

5) Result Table

Best PSD	
Freq(Hz)	Accel(G^2/Hz)
1	0.009796
5.975	0.0152
1e+04	6.105e-09

Table 2. Best PSD table for Bump test

6) Interpretation

The vibration analysis indicates a primary energy peak between 6 and 12 Hz, which is typical of suspension and vehicle body movement. A smaller secondary increase between 40 and 80 Hz may be associated with drivetrain or structural vibrations. Over ten test runs, the PSD curves remain highly consistent up to approximately 80 Hz. Some variations occur above 150 Hz, but it remains within the expected 99/90% statistical limits. A few isolated peaks emerge above 200 Hz, though they have low energy and are likely caused by minor noise or local effects.

The final P99/90 envelope, with a GRMS of 0.397 g, successfully incorporates all test runs without being overly conservative. It maintains the original shape and key frequency changes of the source data, demonstrating that the processing preserved the essential characteristics of the vibration environment.

7) Comparison with literature

These results are consistent with existing literature and standards. Kim et al. (2013) [28] observed that most vibration energy in vehicles is concentrated between 5 and 15 Hz, which aligns closely with the dominant 6–12 Hz band identified in this study. Similarly, ISO 2631-1 (1997) [29] highlights this frequency range as critical for assessing ride comfort and component performance. Furthermore, the transportation spectrum defined in MIL-STD-810H [30] for cargo vehicles specifies a GRMS level of 0.5 g, with spectral breakpoints at 10, 60, and 200 Hz, and a main energy peak at around 8 Hz.

In comparison, the test level obtained in this study is higher, which is reasonable given the harsher road conditions and the sensor's placement directly on the vehicle chassis. This supports the validity of the envelope while reflecting the intended severity of the test environment

8) Implications

The developed envelope is suited for laboratory-based vibration testing and simulation. It accurately reflects real-world conditions while maintaining sufficient safety margins and test repeatability. As such, it can serve as a reliable input for accelerated durability tests of chassis-mounted components. The profile is beneficial for identifying potential issues in mounting systems or stiffeners that may resonate within the dominant 6–12 Hz and secondary 50–70 Hz frequency ranges. Given the energy distribution and GRMS level, the vibration environment corresponds to a paved route with frequent speed bumps, representing moderate to severe operational conditions.

One limitation of the current profile is that it captures vibration only in the vertical axis, which may exclude critical information from lateral or longitudinal inputs in some applications.

4.3.2 Acceleration and brake test results

1) All iterations

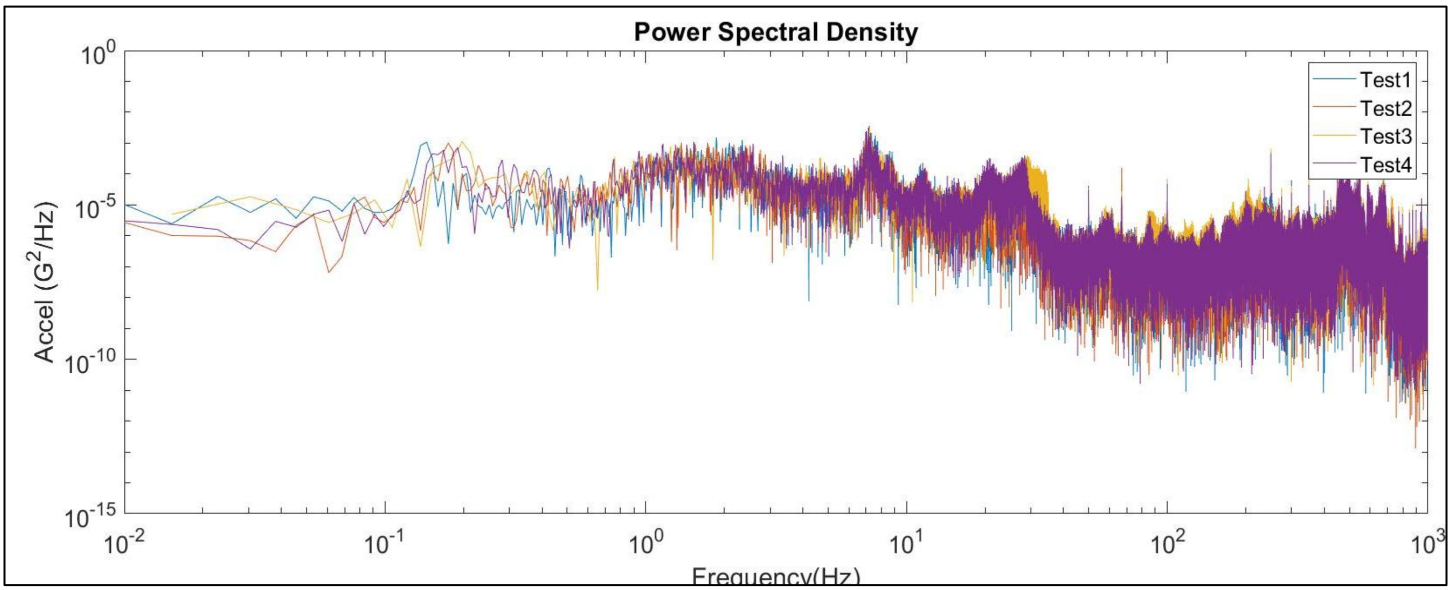

Figure 26. All iterations, Acceleration and brake test

2) Generated Envelope with 99/90% confidence level.

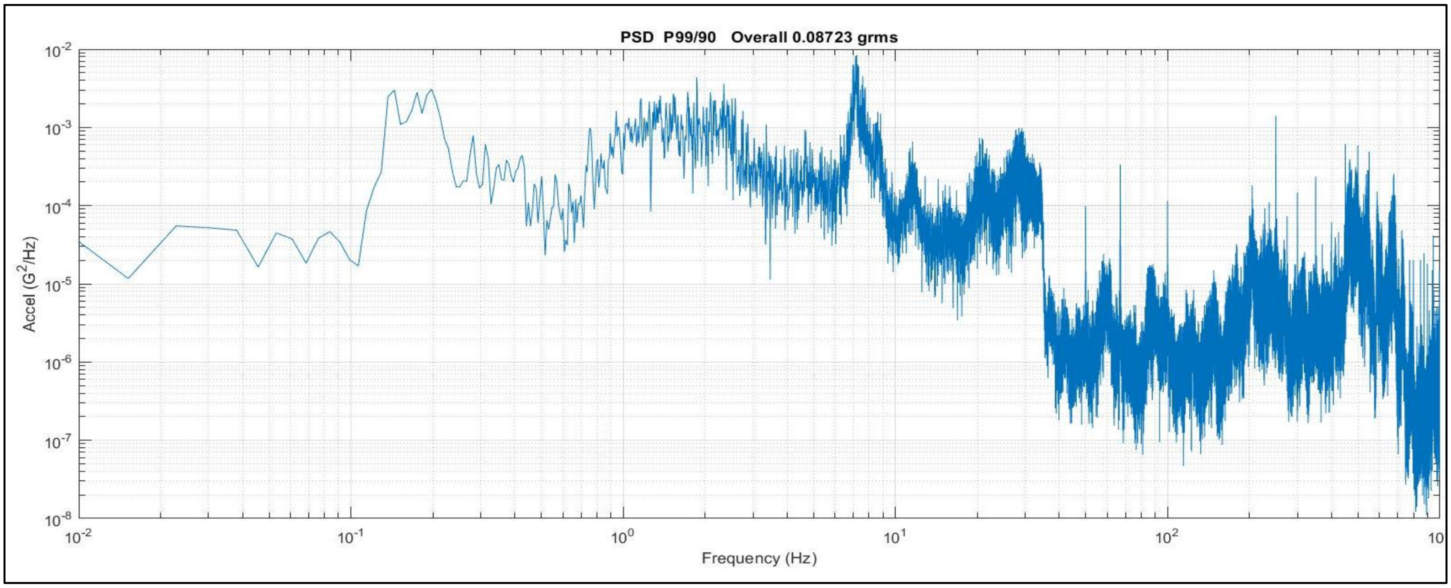

Figure 27. Generated Envelope Acceleration and brake test

3) Envelope compared to previous PSD.

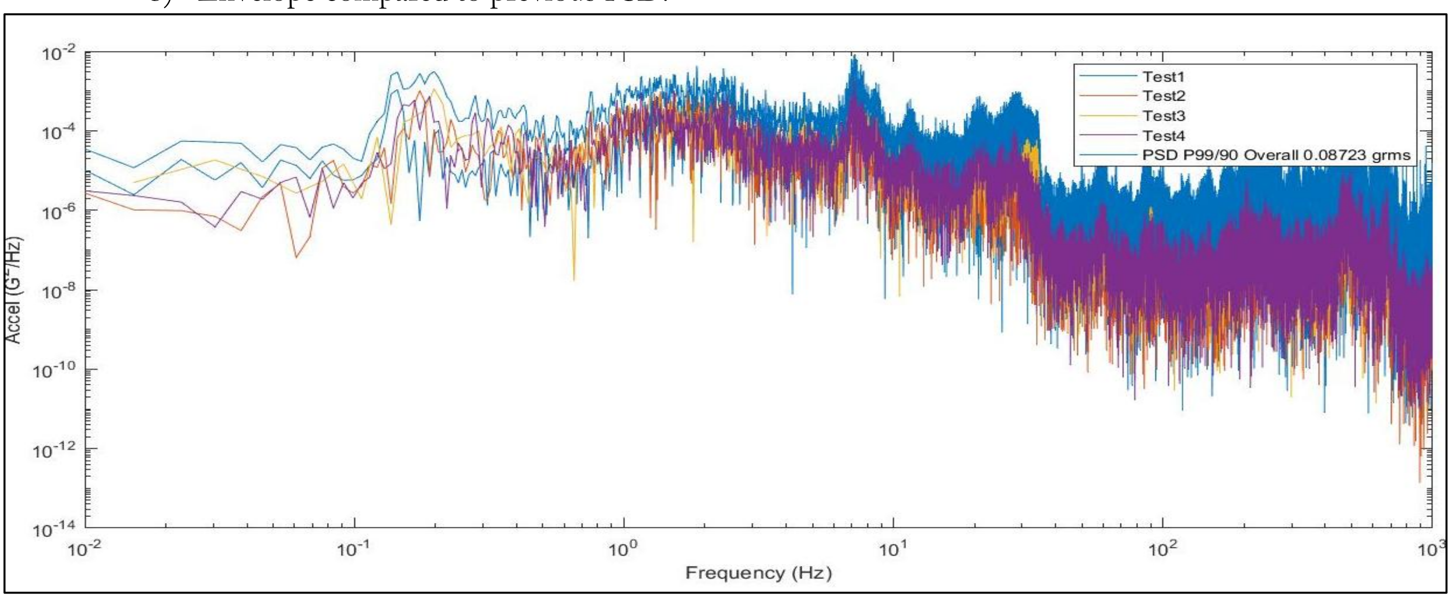

Figure 28. Envelope comparison Acceleration and brake test

4) Final Envelope and representative 90/90% confidence level

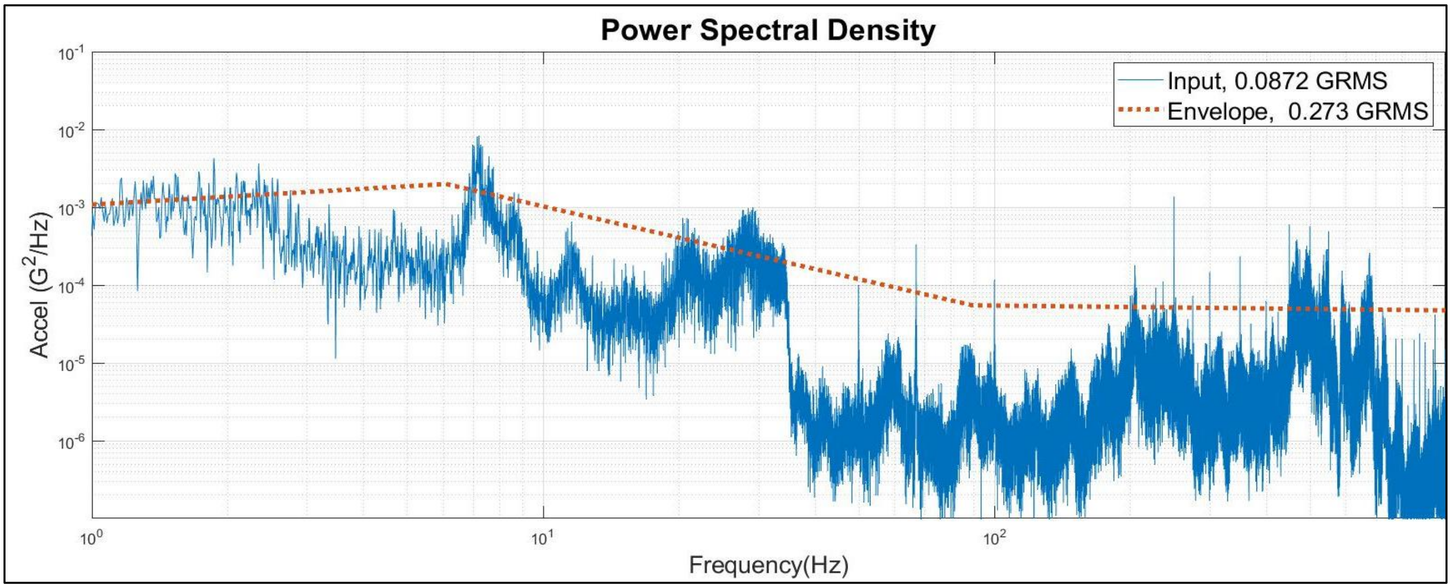

Figure 29. Final Envelope Acceleration and brake test

5) Result Table

Best PSD	
Freq(Hz)	Accel(G^2/Hz)
1	0.001083
6.086	0.001988
89.16	5.491e-05
996.4	4.727e-05

Table 3. Best PSD table for the Acceleration and brake test

6) Interpretation

The vibration profile from this test displays a broad peak between 9 and 15 Hz, with a secondary concentration of energy observed between 25 and 40 Hz. Above 120 Hz, the spectral density decreases significantly, indicating limited high-frequency content. The four test runs show an almost identical pattern, demonstrating excellent repeatability and stability in the measurement conditions.

The initial P99/90 envelope, calculated at 0.087 g RMS, was later adjusted to a final envelope of 0.273 g RMS to ensure full coverage of all traces while retaining statistical relevance. Notably, there are no spurious peaks, and high-frequency noise is negligible, confirming the cleanliness of the data. The overall spectral shape closely preserves the morphology of the field measurements, supporting the integrity of both the acquisition and processing methods.

7) Comparison with literature

This result aligns well with existing standards and reported data. SAE J1455 [31] recommends vibration testing over the 5 to 500 Hz range for ground vehicles. Although the measured profile in this study spans from 5 to 120 Hz, it captures the most relevant portion of the spectrum for chassis-mounted components. The final envelope level of 0.27 g RMS is consistent with values documented during braking events in heavy trucks, further supporting the profile's representativeness for dynamic loads encountered in real-world operations.

8) Implications

The resulting vibration profile is suitable for simulating repetitive start-and-stop conditions, making it a valid reference for laboratory testing in urban or inter-urban heavy-traffic scenarios. The observed frequency content suggests potential relevance to flexural fatigue in wiring harnesses and solder joints, particularly due to the repeated low- and mid-frequency excitation. This makes the envelope valuable for early-stage design validation and reliability testing of sensitive electronic or structural components. For future studies, the use of triaxial measurements is recommended to capture vibration inputs across all axes and provide a more comprehensive understanding of the operational environment.

4.3.3 Continue acceleration test results

For this test, a single sample was collected, with a total duration of 29 minutes and 6 seconds. The recording represents a short intercity trip along a heavy-duty highway under optimal driving conditions, with the vehicle operating at full battery charge. As only one run was available, it was not necessary to generate a statistical envelope to represent multiple traces. Therefore, the corresponding steps for envelope consolidation were omitted in this case.

1) Final Envelope and representative

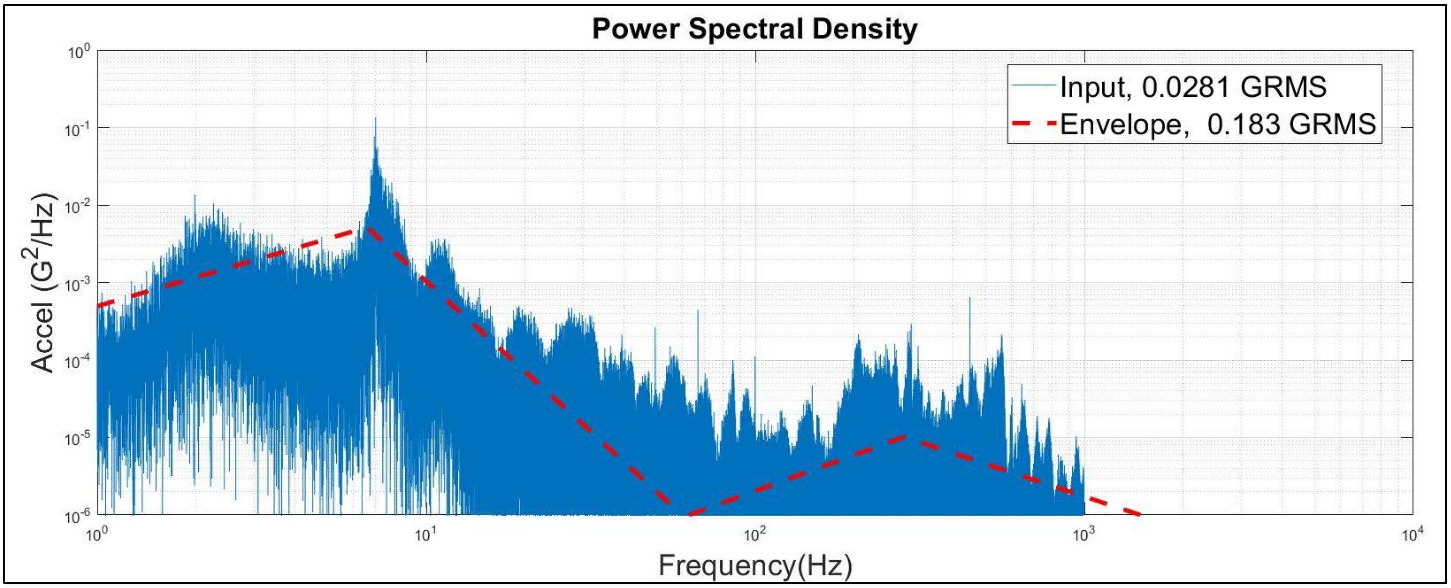

Figure 30. Final Envelope continues acceleration test

2) Result Table

Best PSD	
Freq(Hz)	Accel(G^2/Hz)
1	0.000495
6.605	0.005154
60.74	9.47e-07
283.3	1.018e-05
1e+04	6.806e-08

Table 4. Best PSD table for the continue acceleration test

3) Interpretation

The continuous acceleration test reveals a primary energy band between 8 and 11 Hz, accompanied by a secondary band spanning 60 to 90 Hz, with residual energy extending up to 1 kHz. The test runs show excellent consistency, clustering closely with deviations of less than ±2 dB. A slight notch is observed between 280 and 300 Hz; however, this feature is fully encompassed within the final envelope. The final vibration curve, with a GRMS value of 0.183 g, accurately reproduces the tri-segment spectral slope, maintaining fidelity to the original field data.

4) Comparison with literature

Published studies on continuous transport vibrations report GRMS levels typically ranging from 0.15 to 0.25 g. [32] The measured value of 0.183 g RMS in this test falls squarely within this range, confirming that the derived envelope is representative of typical vibration exposure encountered during sustained vehicle operation.

5) Implications

The vibration profile is well-suited for burn-in and accelerated testing of cab-mounted electronic components, providing a realistic representation of long-haul highway operation conditions. It enables targeted tuning of isolators around the key frequency of 10 Hz to improve vibration isolation effectiveness. Additionally, consideration should be given to vibro-thermal interactions during combined environmental testing, as these can influence component reliability under prolonged exposure.

4.3.4 Off–road test results

1) All iterations

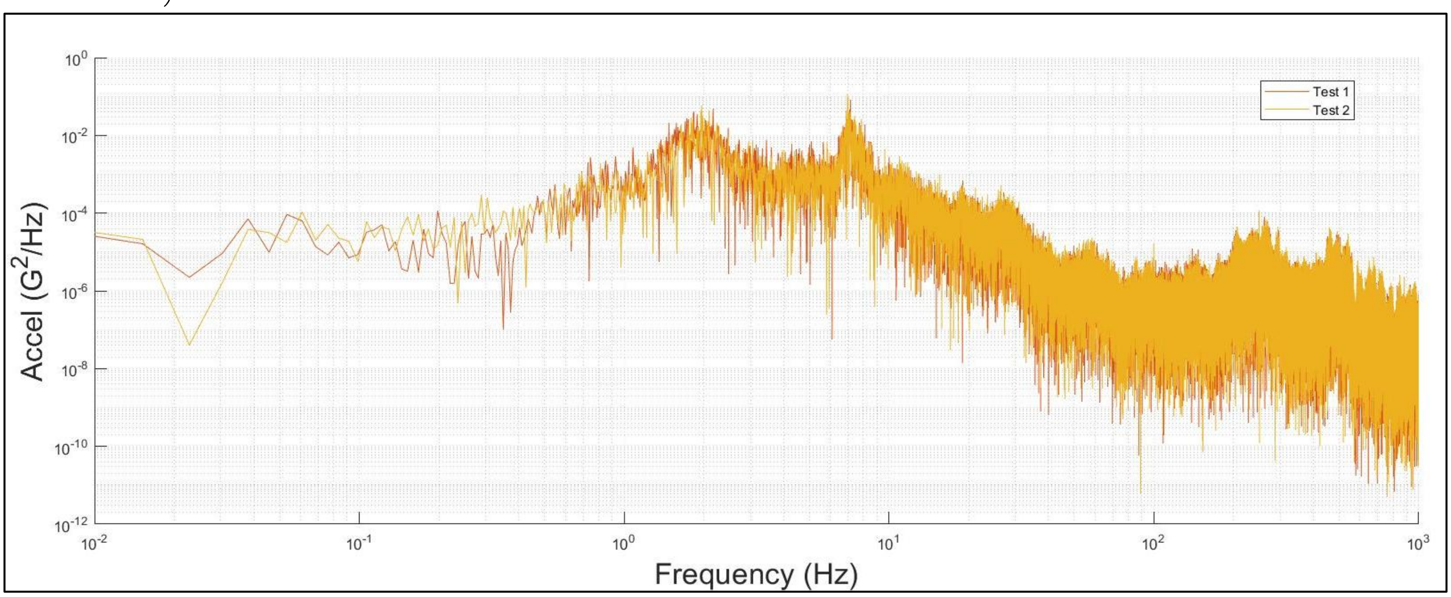

Figure 31. All iterations Off-road test

2) Generated Envelope with 99/90% confidence level.

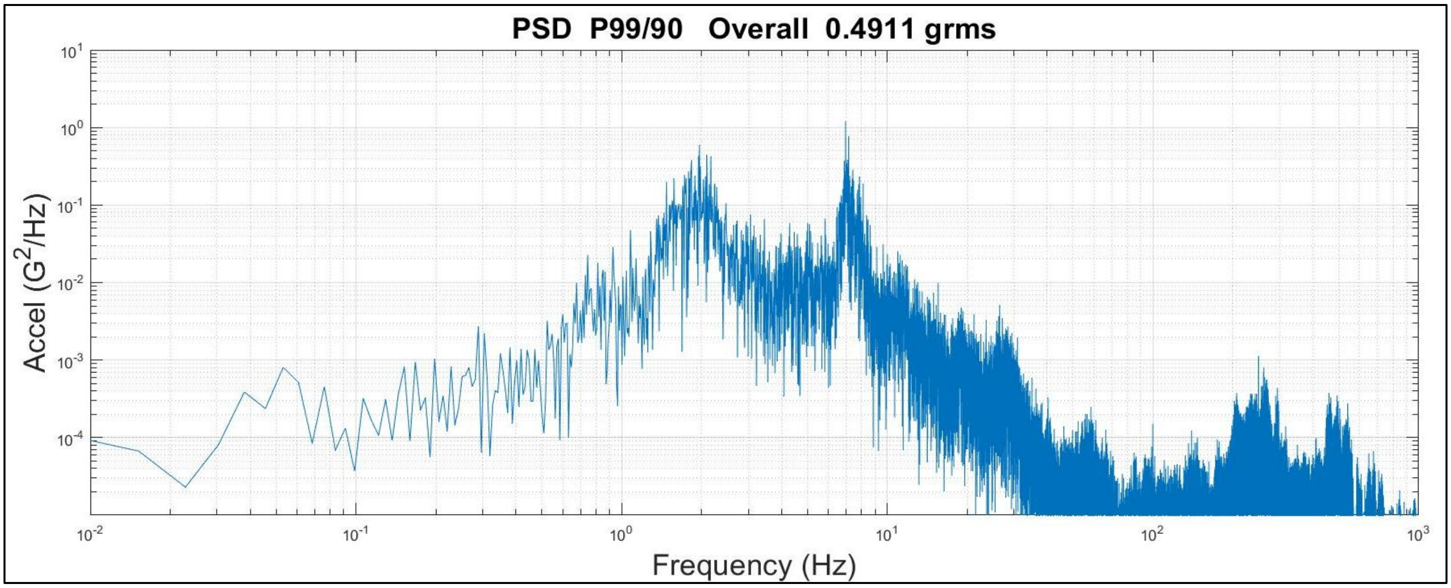

Figure 32. Generated Envelope Off road test

3) Envelope compared to previous PSD.

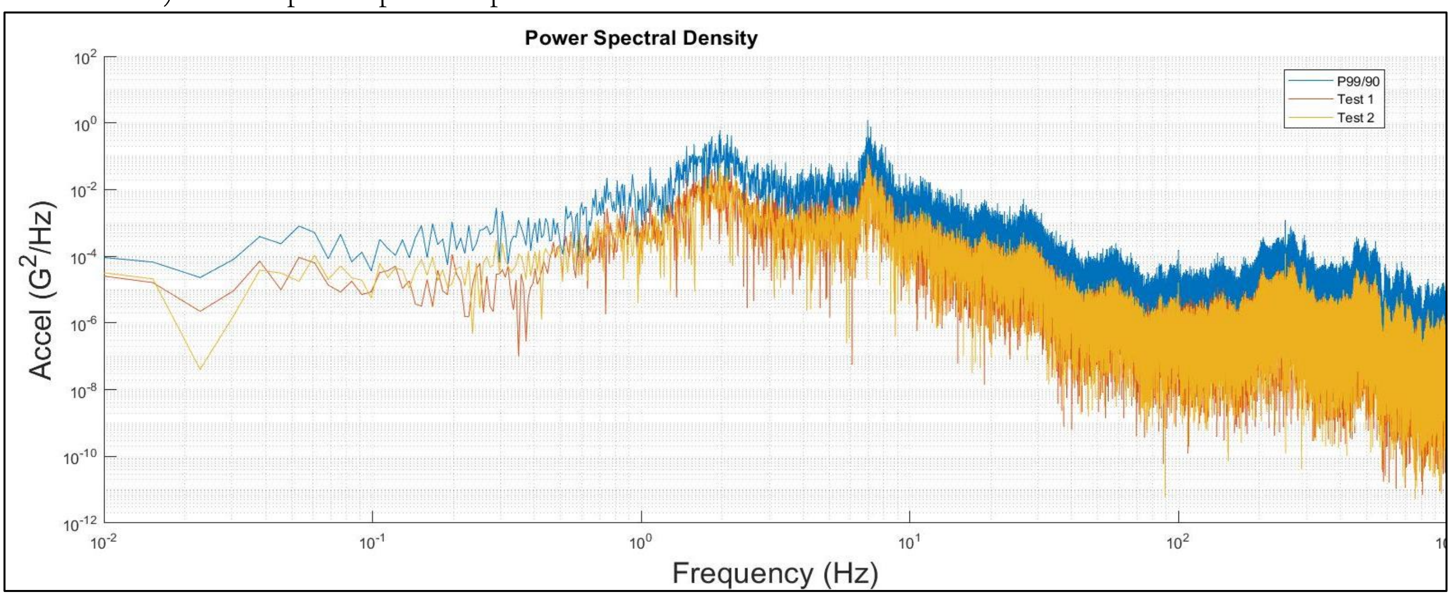

Figure 33. Envelope comparison Off road test

4) Final Envelope and representative 90/90% confidence level

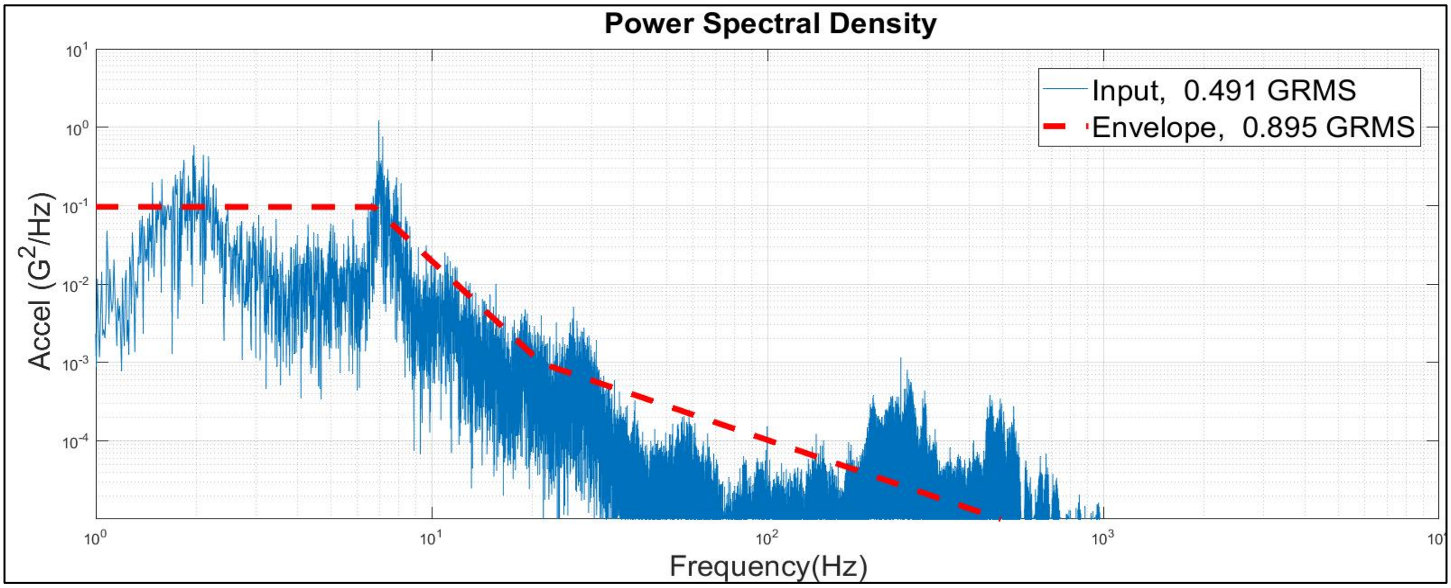

Figure 34. Final Envelope Off road test

5) Result Table

Best PSD	
Freq(Hz)	Accel(G^2/Hz)
1	0.09626
6.723	0.09594
12.4	0.008361
21.31	0.0009651
1e+04	1.265e-07

Table 5. Best PSD table for the off-road test

6) Interpretation

The off-road vibration profile exhibits a dominant peak between 5 and 9 Hz, with a secondary rise at 15 to 18 Hz, followed by a broader energy band spanning 70 to 120 Hz. These features are typical of rough terrain where low-frequency excitations from suspension and body roll dominate, accompanied by higher-frequency structural vibrations. The two recorded runs present similar amplitudes, and the variability remains well-contained within the envelope. No anomalous peaks were detected, and the very low-frequency noise is attributed to natural vehicle roll dynamics. The final envelope, with a GRMS value of 0.895 g, is relatively conservative but appropriate given the harshness of off-road conditions. Importantly, the characteristic -6 dB/octave roll-off beyond 30 Hz is preserved, ensuring fidelity to the field spectrum.

7) Comparison with literature

The measured off-road vibration spectrum is in good agreement with the off-road category defined in MIL-STD-810H, which specifies GRMS levels between 0.8 and 1.0 g with dominant energy below 10 Hz. The primary peak observed in the 5–9 Hz range aligns closely with this specification, confirming that the developed profile accurately reflects the vibration conditions expected in off-road environments [33].

8) Implications

The derived vibration profile is suited for severe durability testing, reflecting the conditions found on unpaved roads or construction sites. Designs subjected to this profile should account for large-amplitude flexural stresses at low frequencies, which can significantly impact component fatigue life. Additionally, careful verification of accelerometer mounting is recommended to ensure accurate data capture, particularly given the high vibration levels encountered in off-road scenarios.

4.3.5 Left and right turning test results

For the left-side turning test, data were collected from a single continuous sample obtained during a sequence of repeated left-hand turns, performed in a roundabout. This approach was selected to create a controlled and repeatable lateral excitation on the same side of the vehicle, allowing for consistent loading conditions and improved signal quality. The total duration of the recording was approximately 10 minutes and 15 seconds, providing sufficient exposure to capture the vehicle's dynamic behavior under sustained cornering. As this test consisted of only one run, it was not necessary to generate a statistical envelope to represent multiple datasets. Therefore, the steps involving envelope construction and consolidation were not applied in this case.

For both the left and right side turning tests, data were collected using a single continuous sample during repeated maneuvers in a roundabout. This method provided consistent lateral excitation on each side of the vehicle under controlled conditions. Each run lasted approximately 10 minutes and 15 seconds. As only one sample was recorded per direction, the steps for statistical envelope generation were omitted.

1) Final Envelope and representative 90/90% confidence level (Left Turn)

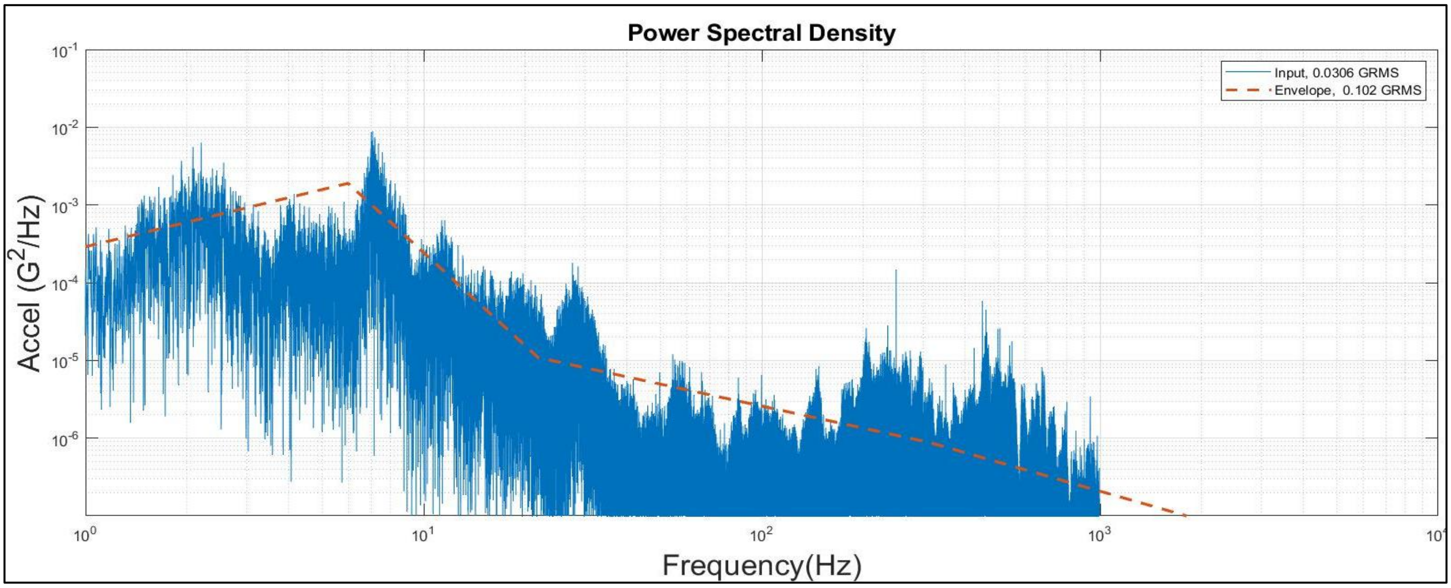

Figure 35. Final Envelope Left turn

2) Result Table (Left Turn)

Best PSD	
Freq(Hz)	Accel(G^2/Hz)
1	0.0002903
5.974	0.001898
21.81	1.087e-05
314.2	8.76e-07
1e+04	1.187e-08

Table 6. Best PSD table for the left turn

1) Final Envelope and representative 90/90% confidence level (Right turn)

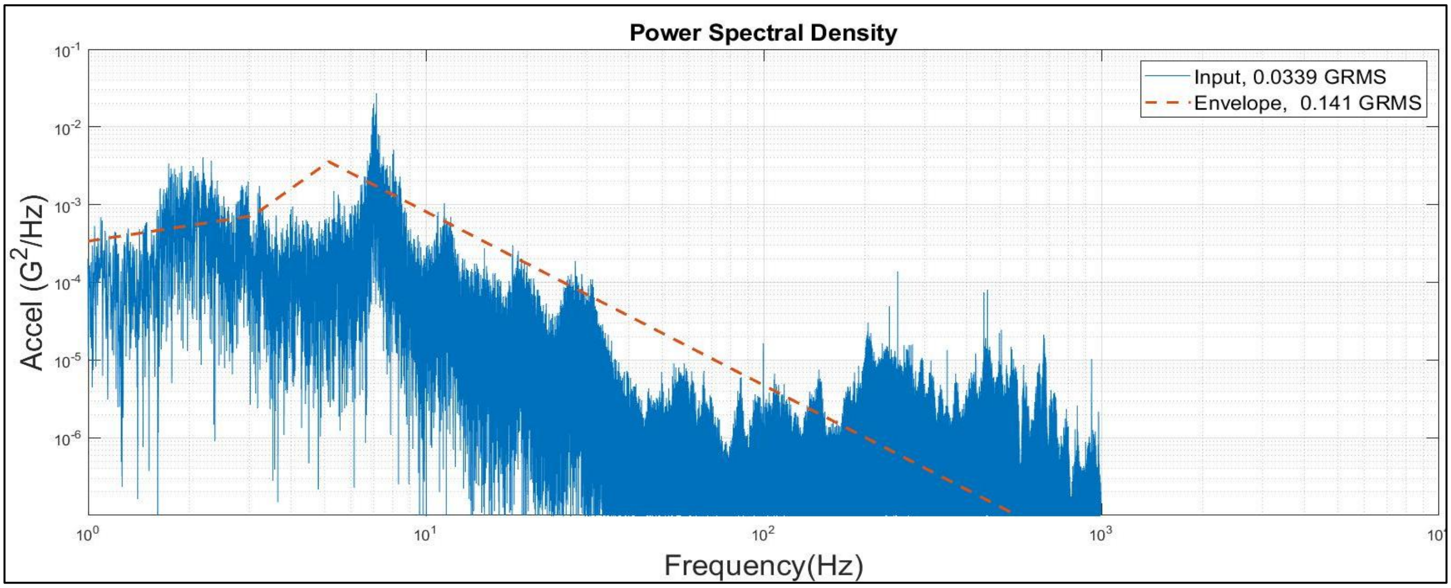

Figure 36. Final Envelope Right turn

2) Result Table (Right Turn)

Best PSD	
Freq(Hz)	Accel(G^2/Hz)
1	0.0003386
3.079	0.0007203
5.158	0.003565
1e+04	1.608e-10

Table 7. Best PSD table for the right turn

3) Interpretation (both)

The dominant vibration energy was observed around 6 Hz, with a peak PSD value of approximately 0.001898 G²/Hz. For comparison, the right-turn test exhibited a similar dominant frequency at 5.158 Hz but with a higher amplitude of 0.003565 G²/Hz. Both results indicate that most of the vibrational energy is concentrated in the 1–10 Hz range, which is consistent with expected chassis and suspension dynamics during sustained cornering maneuvers. Although only a single run was conducted for each turning direction, the controlled roundabout setting and consistent test duration of 10 minutes and 15 seconds lend credibility to the captured data.

The PSD plots for both directions display the anticipated high-frequency roll-off, with no abnormal spikes or artefacts, suggesting clean signals and correct accelerometer installation. While a statistical envelope was not generated due to the single-run nature of the tests, the red envelope line shown on the plots fits the measured data well and offers a reasonable representation of the vibratory environment. The envelope maintains the spectral shape of the original signal, ensuring fidelity and accurately depicting the vibrational behaviour observed. The dominance of the 1–10 Hz frequency band aligns with findings reported in vehicle dynamics literature, particularly in studies focused on lateral structural excitation. Minor discrepancies between left and right turns could be attributed to specific vehicle factors, such as tire type, axle configurations, or sensor placement.

From a practical standpoint, both vibration profiles are suitable for use as input in laboratory testing, particularly for simulating sustained lateral vibrations encountered in roundabouts or tight cornering situations. Notably, the right-turn profile, with a GRMS value of approximately 0.141 g, represents a more severe loading case. Design teams should carefully assess the impact of these lateral vibrations on components such as mounts, electrical connectors, and electronic modules. Taking in consideration that batteries for cab modules, air tanks and dryer is in this axle, can lead to believe the charge distribution of components caused this reaction. Special attention should be given to structures with resonances below 10 Hz, as these may be more susceptible to fatigue or failure under repeated lateral excitation.

The measured profiles are representative of environments characterized by frequent low-speed turns, such as urban streets, logistics hubs, loading yards, or transport terminals. For further validation and to increase statistical robustness, it is recommended that future studies perform multiple runs for each turning direction. Additionally, expanding the analysis to include vertical and longitudinal vibration measurements would enable a comprehensive three-dimensional assessment of the vehicle's dynamic environment, enhancing the accuracy of simulations and durability testing.

4) Comparison with literature

The vibration measurements recorded during the left and right turn tests show good alignment with values reported in established literature. Specifically, the GRMS level of approximately 0.14 g observed in the right-turn test falls comfortably within the typical range of 0.1 to 0.3 g cited for lateral maneuvers in commercial vehicles, as documented in SAE J1211 (2009). This standard outline recommended environmental practices for electronic equipment design, emphasising that lateral vibrations during cornering can be significant contributors to mechanical stress, particularly in components mounted on chassis or suspension systems.

Similarly, Davis (2001) highlights that lateral dynamic loads are critical design considerations, especially for systems sensitive to cyclic stress and fatigue. [34] The consistency between the measured PSD and GRMS levels and those indicated in the literature reinforces the validity of the test data collected in this study. It confirms that the vibration environment captured during the roundabout tests is representative of real-world conditions likely to be encountered by heavy-duty electric vehicles in urban or industrial applications. Furthermore, this agreement suggests that the developed vibration envelopes can serve as reliable inputs for laboratory simulations, component testing, and design validation processes aimed at ensuring durability and operational safety.

5) Implications

The vibration data gathered during both left and right turn tests hold important implications for the design, testing, and operational management of heavy-duty electric vehicles. The measured vibration levels, particularly the dominant energy between 1 and 10 Hz, highlight the need for careful evaluation of components and mounting systems that could be susceptible to lateral loading. Structures such as lateral mounts, electronic modules, and electrical connectors should be assessed for potential resonances and fatigue risks within this frequency range.

The higher GRMS level observed during right turns suggests that certain manoeuvres may impose more severe lateral stresses, warranting specific attention in durability assessments. From an operational perspective, the data indicate that vehicles operating in urban environments, logistics hubs, or industrial facilities, where frequent low-speed turning is common, may experience repeated exposure to these vibration conditions. This underscores the importance of incorporating such profiles into laboratory simulations and accelerated testing to ensure component reliability. Additionally, integrating this vibration data into predictive maintenance strategies could help identify parts at greater risk of wear or failure, enhancing vehicle uptime and reducing unexpected service costs. Overall, the findings provide valuable input for both product development and operational planning, contributing to safer and more robust electric truck designs.

Chapter 5: Conclusions

This research has successfully established a robust and repeatable methodology for capturing, processing, and simulating real-world vibration profiles. The approach closes the gap between uncontrolled field conditions and laboratory-based simulation by translating vibration signals into statistically helpful envelopes using Power Spectral Density (PSD) and Vibration Response Spectrum (VRS) techniques. These spectral envelopes not only matched the general characteristics outlined in existing industry standards but also provided enhanced fidelity by reflecting more realistic and nuanced operational stress patterns. This methodological improvement is particularly significant for the development and testing of battery support systems, where dynamic loading is a critical concern.

The use of high-precision accelerometers proves effective for gathering quality data across a variety of driving scenarios, with a focus on vertical vibration in this phase of the study. Despite using single samples in some cases, the data acquisition and processing workflows remained consistent, enabling statistically consistent analysis even with limited datasets. The envelopes generated served as reliable inputs for potential durability and accelerated life testing procedures. This alignment with real-world vehicle behavior ensures that component testing better reflects operational demands.

The methodological framework presented in this thesis contributes to the emerging body of knowledge around vibration characterization in electric commercial vehicles. It sets a precedent for how field data can inform simulation and testing protocols, particularly in applications where standardized profiles may not sufficiently represent newer vehicle architectures. By focusing on the battery structure—a critical subsystem in electric vehicles- the study offers a pathway towards safer, more resilient, and performance-optimized designs.

This work enhances the credibility of laboratory testing by grounding it in measurable reality, allowing manufacturers to refine product reliability without relying solely on conservative or generic test standards. The proposed vibration modelling approach has the potential to become a standard reference for future studies and industrial practices within the domain of electric vehicle development.

5.1 Recommendations

Several practical recommendations can guide future studies and real-world applications to follow the findings of this thesis. First, the inclusion of tri-axial or multi-axis accelerometers is strongly encouraged. These sensors would capture vibration data not only in the vertical direction, but also in the lateral and longitudinal axes. This measurement capability would provide a more comprehensive picture of the vehicle's dynamic environment in situations involving turns, uneven surfaces, or combined loads. The spectral envelopes generated would more accurately reflect the true operational conditions experienced by the vehicle and its components.

Another important recommendation is to approach the range of vehicles and configurations included in future test campaigns. Testing across various truck utility configurations, load levels, and suspension setups would help build a more diverse and representative set of vibration profiles. This would enable the creation of a comprehensive database of operating conditions, serving as a reference for engineers working on various vehicle types or subsystems. Having access to custom vibration profiles based on specific use cases, such as urban delivery, long-haul transport, or construction site activity, would support more targeted design and testing strategies. Expanding testing to include different road types and driving styles would also improve the dataset's overall relevance and depth.

Integrating real-time telemetry systems during vibration testing is also recommended. By recording vehicle parameters like speed, acceleration, braking, and steering angles alongside vibration data, engineers can better understand the connection between driver inputs and resulting structural responses. This context is particularly useful when analyzing sudden peaks or identifying patterns related to specific maneuvers. Linking vibration behavior to driving events would enhance both data interpretation and system-level understanding, contributing to more informed design decisions.

Finally, it is essential to validate the developed vibration profiles through controlled laboratory replication. Using programmable shakers or vibration tables, engineers can recreate the field-derived envelopes and observe how components behave under repeatable, known conditions. This validation step is key to confirming the usefulness of the profiles for accelerated durability tests. It also allows for a direct comparison between field data and lab results, ensuring the test environment accurately reflects real-world stress levels. Such an approach strengthens the link between simulation, laboratory testing, and actual vehicle use.

5.2 Final Thoughts

This thesis reinforces the essential role of field data in bridging the gap between theoretical design and real-world performance in electric heavy-duty vehicles. Standardized vibration test protocols often fail to capture the full range of dynamic inputs encountered in operational conditions. By implementing a structured pipeline, from data acquisition through spectral envelope synthesis to proposed simulation, this study enhances the accuracy and applicability of vibration testing in both research and industry settings.

Furthermore, the research highlights how sensor selection, data processing, and statistical modelling must work together to produce usable results. The methodology does not just apply to battery systems; its principles could be extended to other subsystems, such as control modules or chassis-mounted electronics, which are also vulnerable to vibration-induced failure. The work also demonstrates that statistically derived envelopes can provide a more efficient and targeted alternative to overly conservative test procedures.

The study supports the integration of empirical data into early-stage design, where the insights can influence choices in material selection, structural layout, and isolation strategies. This reduces the risk of over-engineering or underperformance, supporting both product efficiency and durability. The approach encourages a feedback loop between real-world testing and virtual development cycles.

This work lays the groundwork for a more informed and data-driven approach to vibration testing in electric heavy-duty vehicles. It invites interdisciplinary collaboration across mechanical engineering, data science, and automotive design, fostering more reliable, efficient, and field-relevant engineering solutions.

5.3 Further Research: Replication of the Vibration Profile in Finite Element Simulation

A promising direction for further research lies in applying the developed PSD and VRS envelopes directly within finite element (FE) simulations. By introducing these vibration profiles as boundary conditions in structural or multi-body dynamic models, engineers can simulate the real-world stress distribution and fatigue response of critical components such as battery supports, crossmembers, and suspension arms. This approach would enhance the predictive capabilities of FE analysis, allowing virtual testing to complement, or even partially replace, early-stage physical prototyping.

Simulations informed by real-world vibration data would enable design optimization through material and geometric adjustments. For example, engineers could investigate how small changes in beam thickness, joint rigidity, or mounting isolation affect vibration absorption and stress propagation. The direct mapping of frequency-domain data to time-domain simulation loading is a complex but essential step in achieving true digital validation.

Moreover, using realistic vibration inputs in virtual environments would help uncover failure modes that might not be visible under idealized or standardized loading. This includes resonant conditions, local buckling, and weld fatigue, which are especially critical in the high-load regions typical of heavy-duty electric trucks.

Ultimately, this integration would not only reduce development costs but also improve component safety and durability. It would strengthen the role of simulation as a design validation tool and open the door to the use of advanced AI-driven optimization strategies based on real-world constraints.

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Appendix 1: W8-D40 Vibration Sensor from enDAQ Data Sheet:

W8 Vibration Sensor

$3,899.00 3899.00
Digital Capacitive Accelerometer: ± 40g Battery: 4000 mAh
Storage: 16 GB

The W8-D40 is a wireless vibration recorder with additional environmental sensors. It uploads directly to the enDAQ cloud over WiFi after completing a recording, yet this wireless connectivity can be configured to be off when desired. This model's low cost and robust aluminum enclosure make it ideal for general-purpose vibration testing in harsh environments. The W8 offers an impressive 4,000 mAh battery (our largest) to allow for the longest recording times of our sensors. Product Features Convenient, Adaptable, and Reliable Triggering from Sensors and/or Time Based Standalone Wireless Measurement System Embedded sensors, storage, Wi-Fi connectivity, & power Selectable High-Performance Accelerometers Variable capacitance, piezoelectric & piezoresistive Selectable measurement range from 16g to 2,000gSelectable sampling rate up to 20,000 samples per second to 8 Billion Data Points of Memory Embedded Sensor Suite Gyroscope, magnetometer, pressure, temperature, humidity & light Now includes GPS* and Microphone

Rechargeable Battery Life of Many Days

Extend battery life with triggering and/or external power.

Simple USB Interface for Download & Charging

NIST Traceable Calibration | Calibration Certificate

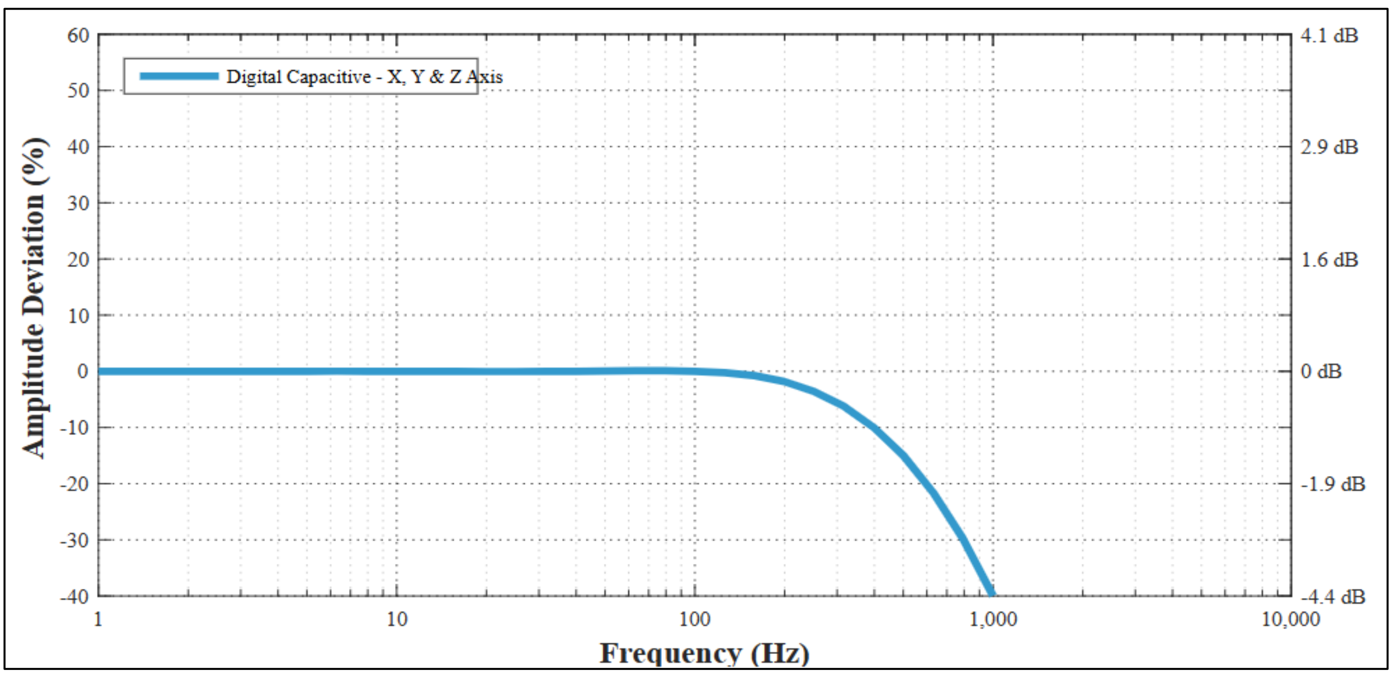
Trusted by Over 2,000 Different Commercial Customers

W8-D40

Accelerometer Specification

Accelerometer Type	Range	Sampling Rate	Bandwidth	Noise	Resolution
Digital Capacitive	± 40g	4,000 Hz	0 to 300 Hz	< 0.01 gRMS	0.00008 g

Frequency Response Plot



Additional Sensor Specifications

Sensor	Measurement Range	Resolution	Sampling Rate
Microphone	105 dB		0 (off) to 20,000 Hz
GPS Location		2.5 m	0 (off) to 1 Hz
GPS Time		60 ns	0 (off) to 1 Hz
Gyroscope	2000°/s	0.06 °/s	0 (off) to 3,200 Hz
Magnetometer	± 1300 µT	0.3 µT	0 (off) to 10 Hz
Temperature	-40 to 85 °C	0.01 °C	0 (off) to 10 Hz
Pressure	1 to 200 kPa	1.6 Pa	0 (off) to 10 Hz
Humidity	0 to 100 %RH	0.04% RH	0 (off) to 10 Hz
Light	0 to > 20 uV	<100 mlx	0 (off) to 4 Hz

Environmental Specifications

Parameter	Range	Notes
Operating Temperature	-40°C to 80°C (-40°F to 176°F)	
Recommended Storage Temperature	15°C to 30°C (59°F to 86°F)	Recharging Temperature 0°C to 45°C (32°F to 113°F)
Humidity	0 to 95 %RH	Non-Condensing
Pressure	20 kPa to 110 kPa (2.9 psi to 16.0 psi)	Absolute Pressure
Shock Limit	>1,000 g	Refer to Shock Report (PDF)
No Electric Field Susceptibility	2 MHz to 18 GHz @ 200 V/m	Refer to EMI Test Report (PDF)
No Magnetic Field Susceptibility	30 Hz to 100 kHz	Refer to EMI Test Report (PDF)

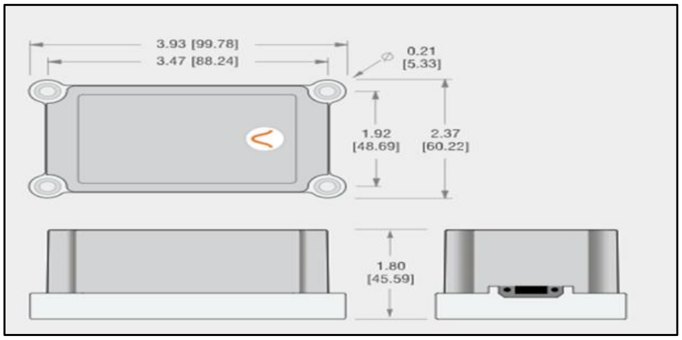
Battery & Storage Performance >> Battery Specifications >> Battery Life Estimator

Battery performance is heavily dependent upon the device configuration (sensor sample rates and triggers), battery age (including charging cycles), temperature, and WiFi interference/strength. The following table provides the battery life and storage capacity of this device, assuming it has a relatively new battery and it is at room temperature. When showing performance, it assumes all sensors are on at the default sample rate, with the main

Sample Rate	Storage Capacity	Continuous Recording	Main Accel. Trigger	2nd Accel. Trigger	Periodic/Time Trigger
50 Hz	64 days	11 days	35 days		2.8 years
200 Hz	40 days	11 days	35 days		2.8 years
800 Hz	15 days	10 days	35 days		2.6 years
4,000 Hz	4 days	8 days	35 days		2.3 years

accelerometer sample rate driving performance. **It also assumes wireless upload is turned OFF. If the device is uploading to the cloud after every recording, assume a battery life of 50% as listed below.** With triggers, it assumes the device is in trigger mode 99% of the time. Here are some additional resources

Dimensions



Mechanical Specifications

Mass	250 grams
Case Material	Aluminum Base, Polycarbonate Top
Mounting - Screw	10-32 Bolts (23 ft-lb)
Mounting - Tape (Double Sided)	3M 950 Tape
Length	99.8 mm (3.93")
Width	58.6 mm (2.31")
Thickness	45.6 mm (1.80")
Ingress Protection	IP 50 (Dust Protected)

Appendix 2: Code used in MATLAB to interpolate matrix

```
% Define batch list for the 10 files
batch_list = {'TOPES1Z.mat', 'TOPES2Z.mat', 'TOPES3Z.mat', 'TOPES4Z.mat', ...
'TOPES5Z.mat', 'TOPES6Z.mat', 'TOPES7Z.mat', 'TOPES8Z.mat', ...
'TOPES9Z.mat', 'TOPES10Z.mat'};
% Load the first file and extract the frequency as the reference
data = load(batch_list{1}); % Load the first file
fieldname = fieldnames(data); % Get fieldnames of the loaded data
TOPES1Z = data.(fieldname{1})% Extract the data from the structure
common_freq = TOPES1Z(:, 1);   % Extract the frequency column
combined_matrix = common_freq;
% Loop through the batch list, load each file, and interpolate
for i = 1:length(batch_list)

    % Load current matrix
    data = load(batch_list{i});  % Load the current .mat file into a structure
    fieldname = fieldnames(data); % Get fieldnames
    current_matrix = data.(fieldname{1})% Extract the data from the structure

    freq = current_matrix(:, 1);    % Frequency column
    PSD = current_matrix(:, 2);    % Acceleration column (G^2/Hz)

    % Interpolate acceleration to match the common frequency
    PSD_interp = interp1(freq, PSD, common_freq, 'linear', 'extrap');

    % Append the interpolated acceleration data as a new column
    combined_matrix = [combined_matrix, PSD_interp];
end

% Save the combined matrix into a new .mat file
save('combined_matrix.mat', 'combined_matrix');
```