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ENHANCING VEHICLE WHEEL SUSPENSION TEST EQUIPMENT THROUGH TAGUCHI METHOD FOR OPTIMIZATION

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The study demonstrates a significant advancement in vehicle suspension testing by utilizing the Taguchi method for optimization. The suspension system determines a vehicle's performance, directly affecting ride comfort, handling, and safety. The research presented in this study highlights a potentially effective method for enhancing suspension testing. The research systematically investigates the complex network of factors influencing suspension behavior using the Taguchi method, a robust optimization technique. The analysis includes examining road surface conditions, passenger weight variations, and tire pressure fluctuations. The objective is to design a suspension system that provides both comfort and stability without making any concessions, regardless of the obstacles encountered on the road. The car utilized for this research is an Altis sedan equipped with tires with a 205/55 R16 profile. The study's findings indicate that factor A, which represents embankment height, significantly impacts 56 % of road irregularity management and the maintenance of a stable driving experience. The dynamic load factor (Factor D) contributes significantly to the vehicle's overall stability and ride quality, accounting for 43 % in different scenarios. Based on the given framework, it can be observed that the variables B (tire pressure) and C (passenger weight) significantly influence suspension vibration, resulting in a reduction of below 0.1 %. While the research results presented here only cover a subset of automobiles, the methodology employed can be used to deal with similar problems in other vehicles

Keywords: Taguchi method, vertical dynamic loads, vehicle body weight, suspension, fast Fourier transform

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1. Introduction

The suspension system of a vehicle is a crucial element that is responsible for ensuring a smooth and stable ride experience for passengers. The component in question plays a pivotal part in the preservation of the vehicle's stability and control. The major purpose of this component is to mitigate the impact of shocks and vibrations resulting from irregular road surfaces and dynamic loads [1]. This feature aims to enhance both the comfort and safety of driving. Given the ongoing progress in automotive technology, it is imperative to optimize suspension systems in order to adequately meet the evolving demands and expectations of vehicle users.

Regular road vehicle activity causes variable dynamic loads. Loads are caused by dynamic load magnitudes, overloading (OL), and repetitive loading [2]. Vehicle weight and wheelbase weight distribution determine loading fluctuation. Traffic volume (measured in automobiles per hour) for different types of vehicles, vehicle contact time, and traffic flow all affect repeated loading (RL) scenarios. Dynamic road pressures result from light, medium, and heavy autos. Complexity is needed to investigate all factors affecting vehicle weight fluctuation. Detailed, complicated suspension system examination is necessary to improve efficiency [3]. The restrictions require a highly effective optimization strategy to address the suspension system's dynamic loads and vibrations. These factors directly affect road surface. To achieve optimal results, optimization must manage complicated component interactions. The vehicle weight distribution, road condition, traffic patterns, and suspension component stiffness [4].

Each vehicle wheel needs well-designed springs and shock absorbers to lessen vertical dynamic loads on the roadbed. According to references, spring, and shock absorbers support the vehicle's weight and provide a smooth ride [2]. Bumping, potholes, and uneven roads require a robust suspension system. Spring and shock absorbers distribute vehicle weight and dampen vibrations and jolts collaboration stabilizes and comforts travelers [5]. Suspension performance depends on springs and shock absorbers. The shock absorber's road surface control depends on the tension spring's stiffness [6]. Stiff tension springs can make shock absorbers struggle to release impact energy, causing an unpleasant ride. Too much vertical movement from a mild tension spring can make the ride unstable and bouncy. To balance road-holding performance and passenger comfort, spring rigidity, and shock absorber efficiency must be balanced [7].

Effective optimization in Taguchi's experiment, the optimal response value is found. A complex investigation was utilized to evaluate the targeted reaction. Each Taguchi optimization stage – design-system, parameter, and tolerance – is crucial [8]. With integrated design, Taguchi improves product performance and reduces manufacturing variability. Methodical planning yields the best results. This powerful optimization technique is widely utilized in the accuracy, effectiveness, and perfection-focused automotive, aerospace, electronics, and manufacturing industries [9]. In this study, Taguchi optimizes suspension test equipment for a vehicle wheel component. The Taguchi statistical strategy is famous and reliable. This enhances product performance, quality, and dependability while decreasing costs and resources in engineering [10]. To find the ideal suspension test equipment arrangement, apply the Taguchi method. Strengthen vehicle wheel assemblies and reduce vibrations. The study investigates how many factors affect the suspension system by finding the strongest variables.

The selection of an optimization method, such as Taguchi, should be supported by a thorough analysis of the problem's characteristics and the desired optimization objectives. Analyzing the advantages of the Taguchi method compared to other optimization techniques, identifying the scenarios in which it is most beneficial, and discussing the key factors that should influence its selection. The effectiveness of the Taguchi method is particularly notable in situations where multiple factors or variables are involved [10]. A fractional factorial design systematically investigates a wide range of parameters while minimizing the required experiments. The efficiency of this approach is particularly advantageous when dealing with a large number of factors.

Taguchi's emphasis on robustness makes it applicable when the objective is to identify parameter configurations that consistently yield optimal performance, even when faced with uncontrollable factors or variations. Consistent product quality is of utmost importance in fields such as manufacturing. Taguchi's expertise in quality improvement efforts is well-established, particularly within the automotive and electronics manufacturing industries. This technique has proven effective in enhancing the efficiency and effectiveness of processes and product designs, leading to notable improvements in quality and reliability.

The Taguchi method continues to be extensively employed by researchers for the purpose of optimizing parameters in engineering systems. An example of an application is inside the suspension system of automobiles, where it is utilized to determine the ideal parameters of the vehicle. An optimally calibrated suspension system possesses the capability to alleviate the adverse impacts of road irregularities, such as potholes and bumps, hence diminishing passenger discomfort and limiting the deterioration of vehicle components. Moreover, the implementation of a suitably optimized suspension system has the potential to enhance the handling and stability of a vehicle, which plays a pivotal role in mitigating the occurrence of accidents and instilling a sense of assurance in the driver. Therefore, research devoted to the optimization of vehicle wheel suspension using the Taguchi method is still relevant.

2. Literature review and problem statement

The suspension system of vehicles is a critical component that directly influences ride comfort, vehicle stability, and handling characteristics [11]. Numerous studies have been conducted to optimize suspension design and performance using various methods and techniques. One notable approach that has gained popularity in recent years is the Taguchi method, known for its ability to identify and optimize the factors affecting product performance efficiently [12].

Due to its systematic and robust nature, researchers have applied the Taguchi method to diverse engineering fields, including automotive and mechanical engineering. The Taguchi method has been used in vehicle suspension systems to determine optimal settings for parameters such as spring rates, damping coefficients, tire pressures, and load distributions. Researchers have successfully improved suspension performance by employing this method while minimizing sensitivity to external disturbances.

In the paper [12], the researchers employed the Taguchi method to integrate vibration testing and robust optimization analysis. This approach allowed for an adequate evaluation of how various factors influence the suspension system's vibration behavior and facilitated the identification of optimal settings to minimize vibrations and improve ride comfort. By using this robust optimization technique, engineers could balance conflicting objectives, such as ride comfort and handling performance, resulting in well-balanced suspension designs. However, it is essential to recognize the assumptions and limitations of the Taguchi method and robust optimization approach, as they may impact the scope and potential challenges of the study's findings. Shedding light on these limitations can aid readers in understanding the study's implications more comprehensively.

The research [12] focuses on the problem of robust optimization, which entails developing a system that can effectively operate under different conditions and handle uncertainties. The study likely concentrates on enhancing the suspension system's robustness to account for variations in road conditions, load, and other relevant factors. Numerous areas warrant further investigation, including the topic of complex road conditions. The study may have overlooked the inclusion of highly intricate real-world road conditions, such as off-road terrains, gravel roads, or notably uneven surfaces.

The potential impact of the suspension's performance under these conditions has not been thoroughly investigated. This section has not been thoroughly investigated due to highly complex and challenging aspects that make comprehensive study difficult. Researchers often opt to simplify complex problems to make them more manageable and feasible to study within the limitations of their research.

The study [13] is an impressive effort focusing on a noteworthy aspect of automotive engineering. The application of the Taguchi method and the emphasis on rear suspension geometry provide valuable insights for optimizing vehicle handling. Improved handling has significant practical implications, directly affecting road safety and the overall driving experience. To enhance the overall contribution of the research to the field of vehicle dynamics and suspension design, it is essential to provide more detailed explanations of parameter selection, real-world validation, and consideration of trade-offs. The study has the potential to provide valuable insights into improving vehicle handling and promoting safer and more enjoyable driving experiences.

The research [13] focuses on a significant issue in vehicle dynamics, which is the challenge of ensuring stable handling, mainly when performing maneuvers like cornering or lane changes. The study likely focused on optimizing rear suspension geometry to improve the vehicle's stability across different driving conditions. The study primarily emphasizes the analysis of rear suspension geometry. One potential area of investigation is the impact of the interplay between front and rear suspension geometry on the overall handling characteristics of a vehicle. The front suspension is an essential component that significantly impacts a vehicle's steering and handling characteristics. The topic of vehicle handling is multifaceted and affected by numerous factors such as suspension geometry, tire characteristics, aerodynamics, and other variables.

The study conducted by the researchers [14] is a significant and noteworthy addition to the field of automobile engineering. It provides valuable insights into the improvement of suspension system resilience. The use of the Taguchi technique, along with a targeted approach toward suspension parameters, offers pragmatic recommendations for attaining consistent and dependable suspension performance. Nevertheless, enhancing the research's overall effect and practical relevance may be achieved by providing more comprehensive explanations of parameter selection, undertaking a thorough analysis of findings, addressing the limits of the Taguchi technique, and doing real-world validation. Considering these factors, the research may serve as a significant reference for automotive engineers aiming to enhance suspension systems and vehicle performance.

The issue examined in this research [14] pertains to the variability of vehicle loads, ranging from passengers to cargo. One of the main challenges is ensuring that the suspension can handle various load conditions while maintaining optimal performance and safety. Vehicle suspensions play a crucial role in a vehicle's overall performance and safety. They are not isolated systems but interact with other vital systems, such as steering, braking, and electronic stability control. These interactions are essential for maintaining control, stability, and responsiveness while driving. Certain studies may not thoroughly investigate the relationship between suspension design and these systems. The complexity of suspension design can lead researchers to simplify their models or experiments to make the research more manageable. The process of simplification may lead to the exclusion of certain elements.

The study mentioned above [15] shows potential in effectively addressing crucial elements of vehicle dynamics and ride quality. The incorporation of various components and the prioritization of enhancing ride comfort are significant contributions. Nevertheless, improving the research's overall effect and practical relevance may be achieved by offering more comprehensive elucidations of parameter selection, validation methodologies, careful evaluation of trade-offs, and the generalizability of results. By examining these many characteristics, the research has the potential to provide significant contributions in boosting the comfort experienced during vehicle rides and developing the design of suspension systems, ultimately leading to superior driving experiences.

Pneumatic actuators are analyzed novelly as vertical dynamic load substitutes in vehicle suspension systems [16]. Medium-weighted wheel combinations are studied to understand how pneumatic actuators can replicate suspension system dynamic loads. The study examines medium-weighted wheel suspension. The specialization provides for a focused examination, but it may limit generalizability to other vehicle types or load conditions. Different vehicle types have different suspension systems, which affects how well pneumatic actuators mimic real-world situations. Further study of pneumatic actuator load simulator restrictions might further benefit the work.

The investigation of optimizing a quarter-car suspension system by utilizing the Response Surface Methodology (RSM) and Taguchi method offers a compelling strategy for improving the operational capabilities of vehicle suspension systems [17]. This study aims to identify the most favorable parameters for the suspension system to enhance ride comfort and handling. This will be accomplished by integrating two widely recognized optimization methodologies. One notable aspect of this study is its utilization of both Response Surface Methodology (RSM) and Taguchi methodologies, which enhances its overall strength. The study uses both methods to attain a more robust and thorough optimization process. Furthermore, the emphasis on a quarter car suspension system is both pragmatic and pertinent since this particular system serves as a vital element in determining the ride comfort of an automobile. The optimization of this system carries significant implications for the enhancement of passenger comfort and safety [18].

Computer-aided engineering (CAE) software is a game-changer in the engineering industry since it allows professionals to run simulations and conduct virtual tests on suspension systems. CAE will enable engineers to explore the subtleties of suspension behavior, giving them unprecedented control over their designs. They can use this dynamic tool to test suspension systems in various conditions, from normal driving to off-roading and other difficult situations. Engineers can go on a scavenger hunt with CAE software, testing the limits of suspension design and performance. The suspension's response to load changes, terrain, and driving styles can be analyzed [19]. Thanks to this deep understanding of system dynamics, engineers can now fine-tune and optimize their designs with previously inconceivable precision and accuracy. The need for expensive physical prototypes and lengthy testing phases can be drastically cut using CAE software to make well-informed judgments early in the design process. This reduces expenses and helps the environment by cutting down on waste and power usage.

The significance of suspension systems in vehicles and the potential advantages of utilizing the Taguchi method for optimization are well recognized. However, a noticeable dearth of research explicitly addresses the optimization of suspension test equipment. The study focuses on the lack of a structured and thorough method for designing and optimizing suspension test equipment for a specific component of a vehicle wheel. The current body of research primarily focuses on enhancing suspension design and tuning parameters while neglecting the crucial aspect of creating appropriate test equipment to assess suspension performance accurately. The lack of optimized test equipment can negatively affect the evaluation of suspension behavior. This can lead to inaccurate design decisions and decreased vehicle performance.

3. The aim and objectives of the study

This study aims to enhance the existing suspension testing technology to develop equipment capable of providing more accurate and consistent evaluations of suspension system performance. This will make it possible to optimize the settings of the equipment used in testing and ultimately contribute to advancing more reliable and efficient testing protocols.

To achieve this aim, the following objectives are accomplished:

– to determine the optimal value of each parameter for suspension vibration: embankment height, tire pressure, payload, and dynamic load;

– to ensure consistent ride comfort and minimal vibration loads for passengers under varying conditions, including changes in embankment height, tire pressure, payload, and dynamic load.

4. Materials and Methods

4. 1. Object and hypothesis of the study

The object of this study is the vehicle wheel suspension test equipment.

The primary hypothesis of this work is focused on the notion that with the use of the Taguchi method and the optimization of specific pivotal parameters in vehicle wheel suspension test equipment, it is plausible to enhance its performance and precision in replicating suspension behavior observed in real-world scenarios.

The research assumes that the parameters being studied, such as mound height, tire pressure, passenger weight, and dynamic load, substantially influence the performance and behavior of the vehicle's suspension system. The assumption serves as the foundation for conducting experiments to optimize these parameters. The current suspension test equipment may have limitations or inefficiencies that could be enhanced. The belief that underlies the objective of the research is to improve the performance of the equipment. The study assumes that attaining optimal ride comfort is a crucial objective in designing vehicle suspensions. The assumption made here is that factors like passenger weight and dynamic load have a direct impact on ride comfort.

The simplifications employed in a research investigation may differ depending on the study's particular objectives, extent, and limitations. A prevalent simplification involves assuming linear relationships between parameters and responses. In actuality, the dynamics of car suspensions exhibit nonlinearity, yet linear approximations are frequently employed to streamline the modeling and analysis process. Simplifying assumptions may encompass the evaluation of suspensions by subjecting them to consistent or idealized road conditions, such as a uniformly even road surface, to isolate and analyze the impacts of individual factors.

4. 2. Material

The material used in this study is essential for investigating and implementing the innovative approach to suspension system testing. Fig. 1 showcases the key components of creating a dynamic and controlled testing environment. Pneumatic cylinders (Fig. 1, *a*) are crucial in generating the necessary vibrations in the suspension system. These cylinders act as vibration triggers, simulating various road conditions and dynamic loads that the suspension may encounter during real-world driving scenarios. Using pneumatic cylinders offers several advantages, including precise control over the magnitude and frequency of vibrations induced in the suspension. This level of control ensures that the testing conditions are repeatable and consistent, enabling researchers to isolate specific factors and accurately assess their impact on suspension performance.

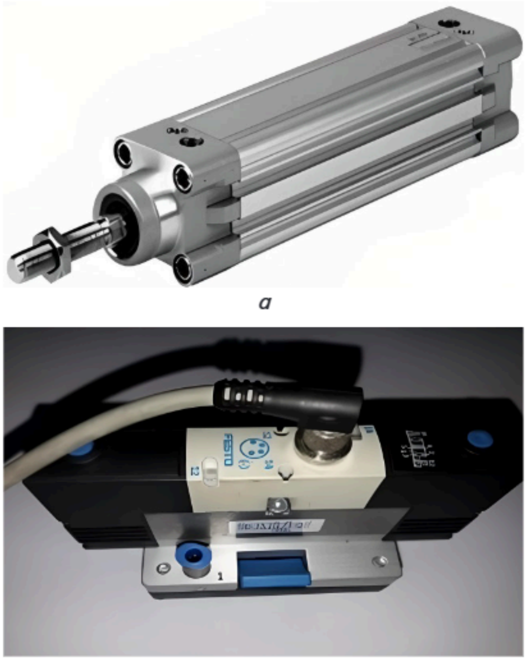


Fig. 1. Displays two components: *a* – a pneumatic actuator; *b* – a memory valve with a 5/2 configuration

Additionally, incorporating 5/2 valve solenoids (Fig. 1, *b*) enhances the pneumatic system's versatility. These solenoids enable rapid and efficient switching of the pneumatic cylinders, allowing for dynamic changes in the vibration patterns. By manipulating the 5/2 valve solenoids, researchers can simulate various road irregularities, such as potholes, speed bumps, and undulations, significantly affecting suspension behavior and passenger comfort. Using pneumatic cylinders and 5/2 valve solenoids as vibration triggers provides a unique and flexible approach to suspension testing. Traditional testing methods may not adequately replicate real-world conditions. Still, this experimental setup enables researchers to mimic a wide range of road surfaces and dynamic loads in a controlled laboratory environment. Integrating pneumatic cylinders and 5/2 valve solenoids as vibration triggers allows for a comprehensive investigation of suspension behavior under varying conditions. Researchers can observe how the suspension system responds to different vibration profiles, helping identify potential areas for improvement and optimization.

4. 3. Experimental setup

The successful method is the force exerted by the cylindrical thorax during the forward step, denoted by the unit N and written as F_{ef}. This force is calculated by subtracting the theoretical force, F_k (N), from the frictional force, R_f (N) [16]. The result is the magnitude of this force. The entire load transfer mechanism against the asphalt road structure can be characterized using the equation of equilibrium of dynamic forces obtained from the Free Body Diagram (FBD) illustrated in Fig. 2 [20]. This equation can be determined by setting the frictional force R_f at a specific value (N) and then using this equation to represent the total load.

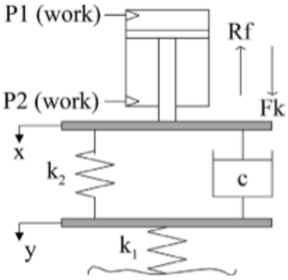


Fig. 2. The experimental loading mechanism of the system

Equations (1) and (2) mathematically express the effective thrust force exerted by the piston of the pneumatic cylinder, which is generated by the air pressure P_2 (bar) [20]. The equations offer a valuable analysis of the forces and dynamic behavior of the pneumatic cylinder in the experimental setup. Equation (1) describes the correlation between air pressure P_2 and effective thrust force F_{ef}, illustrating the direct influence of pneumatic pressure on piston force. Equation (2) provides further insight into the various factors that contribute to the overall system performance, specifically focusing on the dimensions and characteristics of the cylinder and their impact:

$$\text{Compressive force}\left(F_k\right)=\frac{\pi}{4}D^2P_2. \tag{1}$$

$$\text{New compressive force } (F_{p2})=F_{ef}=F_k-R_f=$$
$$=F_k-0.1{*}F_k=0.9{*}F_k, \tag{2}$$

where the force F_k=1.1, $k-2y+c$, y, and the effective force, $F_{ef}=F_{p2}=k-2y+c$, y.

If the cylinder dimensions used in the experiment are set to 0.100 m, then based on equation (2), a compressive force is obtained on the suspension mechanism. The equation suggests that the compressive force, denoted as F_k, is related to the air pressure P_2 in the cylinder. The compressive force (F_k) value can be calculated using the provided relationship: $F_k=785\times P_2$ [5]. This equation indicates that the compressive force is directly proportional to the air pressure P_2, with a constant of proportionality equal to 785.

The dimension D=100 mm corresponds to the diameter of the cylinder, and it plays a significant role in determining the compression force exerted on the suspension mechanism. The diameter of the cylinder influences the effective surface area exposed to the air pressure, directly affecting the overall force generated by the pneumatic cylinder. As the air pressure P_2 varies, the compressive force F_k changes accordingly. Researchers can regulate the compressive force applied to the suspension mechanism by controlling the air pressure. This control over the compressive force is crucial for fine-tuning the suspension system's behavior and optimizing its performance for different road conditions and vehicle loads. Equation (3) shows the new compressive force by suspension mechanism:

$$\text{New compressive force } (F_{p2})=0.9\times 785P_2=$$
$$=707P_2=k_2y+c\dot{y}. \tag{3}$$

When a spring is loaded, it undergoes shortening or deflection due to the law of action-reaction. According to this principle, the load applied to the spring is directly proportional to the magnitude of the deflection and is determined by the spring constant. This relationship between load, deflection, and the spring constant is fundamental to understanding the behavior of the suspension system. In the optimized suspension system context, the average displacement (x) is measured to be 0.009264 m. This average displacement represents the average amount the suspension system compresses or extends during its operation, reflecting its response to external forces such as road irregularities or driving conditions.

Furthermore, the maximum vertical acceleration observed in the optimized suspension system is 15.5707 m/s^2. Vertical acceleration refers to the rate of change of vertical velocity, and this value provides crucial insights into the suspension system's ability to absorb and dampen vibrations and shocks during vehicle operation. Combining the average displacement and the maximum vertical acceleration showcases the suspension system's effectiveness in providing a smooth and controlled ride experience. A well-optimized suspension system ensures that the vehicle's wheels maintain better contact with the road surface, minimizing vibrations and impacts transmitted to the vehicle's occupants.

The test spring utilized in the suspension system mechanism is of the «Helical» type, characterized by specific dimensions and specifications. The key dimensions of the spring include the inner diameter of the coil (Di) measuring 12.985 cm and the outer diameter of the coil (Do) measuring 15.815 cm. Additionally, the diameter of the spring wire (d) is 1.415 cm, and the number of coils (n) in the spring is 5 pieces. The spring material is specified as Chrome Vanadium, ASTM A231. This material choice significantly determines the spring's mechanical properties, including its strength, durability, and performance under varying conditions.

Furthermore, the modulus of stiffness (G) for the test spring is determined to be 7.929×10^{10} Pa, equivalent to 7.929×10^{6} N/cm^2. The modulus of stiffness represents the material's resistance to deformation under an applied load, and it is a crucial parameter for characterizing the spring's behavior. The test spring is classified as a «Helical compression spring» designed to absorb and store energy when subjected to compressive forces. Helical compression springs are widely used in various applications, including suspension systems because they provide support and absorb shocks. The spring constant (k_2) is an essential parameter determining the spring's stiffness. It is calculated using the equation (4) presented in reference [7]. The spring constant quantifies the relationship between the force applied to the spring and the resulting deflection or compression:

$$\text{Spring constant }\left(k_2\right)=\frac{Gd^4}{8n_aD^3}. \tag{4}$$

In general, the vehicle's suspension system is crucial for providing a smooth and controlled ride experience. It typically consists of a spring and a shock absorber arranged in parallel. Each element plays a distinct role in enhancing vehicle dynamics and passenger comfort. The primary function of the suspension system is to support the vehicle's weight, including the body, engine, passengers, and cargo. By effectively distributing and absorbing the weight, the suspension system ensures that the car remains stable and balanced during motion, contributing to better handling and overall safety.

Additionally, the suspension system is responsible for maintaining proper wheel alignment. Proper alignment is crucial for even tire wear and optimal handling characteristics. By keeping the wheels aligned, the suspension system improves tire life and reduces the risk of uneven tire wear patterns. Fig. 3 showcases the passive suspension mechanism and the condition of the vehicle quarter loading structure. The passive suspension system is the conventional type of suspension that operates without active control systems. It relies on the mechanical properties of the spring and shock absorber to provide the desired ride characteristics.

The vehicle quarter loading structure in Fig. 3, *a* illustrates the arrangement of the suspension components for one-quarter of the vehicle. This representation allows researchers and engineers to analyze the suspension's behavior and understand how it interacts with the vehicle's weight distribution. Examining Fig. 3, *b*, it becomes possible to calculate the force acting on the tire using equation (5) [11]. This equation likely represents a fundamental relationship that enables researchers and engineers to quantify the forces at play in the vehicle's suspension system:

$$\text{Acting force } (F_{t1})=F_{ro}=707P_2+(k_1x). \tag{5}$$

Equation (5) likely incorporates several variables, such as the spring constant, damping coefficient, tire characteristics, and the vertical displacement of the suspension. The spring constant and damping coefficient dictate the stiffness and damping characteristics of the suspension system, influencing its ability to absorb shocks and vibrations. On the other hand, tire characteristics play a vital role in determining tire grip and traction against the road surface.

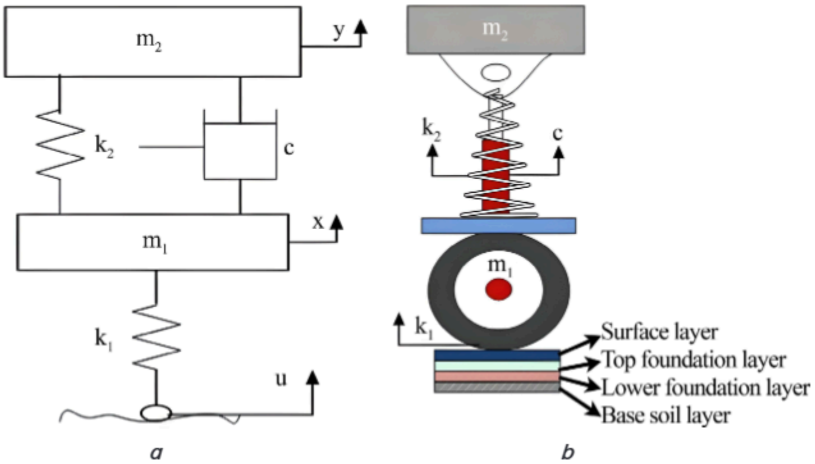


Fig. 3. A schematic representation of the following: *a* – passive suspension model; *b* – suspension unit consisting of a shock absorber, axis, and wheels on road lining structure

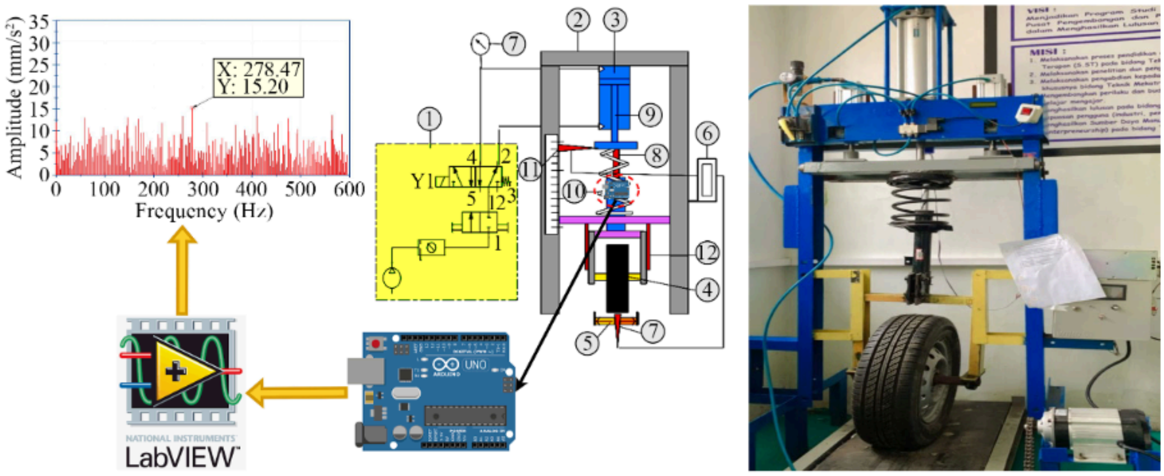
The main components of this study, as illustrated in the research scheme in Fig. 4, *a*, are fundamental to successfully implementing the experimental setup, facilitating data collection and analysis to achieve the study's objectives. The key components include Software LabVIEW, Arduino Uno, Accelerometer MPU6050, and Suspension Test Equipment. To begin with, the data retrieval process is executed by utilizing the Software LabVIEW (1). Acting as the central hub for data acquisition and analysis, the LabVIEW software, running on a laptop, allows researchers to effectively monitor and record various parameters related to the suspension system's performance during testing.

The Arduino Uno microcontroller (2) is a critical intermediary between the LabVIEW software and the experimental setup. It enables seamless communication and control over the Suspension Test Equipment, providing real-time data acquisition and system manipulation capabilities. The Accelerometer MPU6050 (3) is a pivotal sensor that captures and measures the vibrations occurring within the suspension system. Mounted on the Shock Absorber part of the Suspension Test Equipment, the MPU6050 continuously records vibration data, providing valuable insights into the suspension system's response to dynamic conditions. The resulting vibration data is then transformed into a Fast Fourier Transform (FFT) graph (4). This graph presents a comprehensive frequency domain representation of the vibrations, aiding researchers in understanding the suspension system's behavior and identifying potential areas for optimization and improvement.

A key component of test equipment, pneumatic cylinders accurately simulate road conditions and cause suspension system vibrations. This simulation centers on the pneumatic cylinder's pressure and suspension load interaction. Precision pressure regulators control the pneumatic cylinder's pressure settings, the lifeblood of this dynamic system (7). A pneumatic cylinder's force application to the suspension load can be accurately calibrated with an adjustable regulator. Elegant simplicity: pneumatic pressure increases force while decreasing pressure decreases force proportionally – a surprisingly obvious configuration.

Add the MPU6050 Accelerometer (3) to continue our technological trip. This highly sensitive accelerometer acts as our sentinel, measuring suspension vibrations and documenting the suspension's subtle responses to simulated road conditions. LabView receives this rich data stream seamlessly through the microcontroller's clever processing. LabView transforms this plethora of data into compelling insights, enabling real-time suspension behavior analysis. Its well-orchestrated symphony of pneumatic cylinders, precision regulators, accelerometers, and intelligent software lets us investigate, understand, and tune car suspension systems with unparalleled control and precision.

The Prototype of the Suspension Test Equipment, as depicted in Fig. 4, *b*, is a vital aspect of this research, offering a tangible and physical representation of the apparatus used in the experimental setup. This prototype is a valuable tool that allows researchers to conduct thorough assessments of the Suspension Test Equipment's physical characteristics and functionality, ensuring its suitability and accuracy for conducting the experiments.



a *b*

Fig. 4. A schematic illustration of: *a* — the experimental setup; *b* — the experimental test equipment

Fig. 5 presents a crucial aspect of this research, showcasing the creation of the vibration program using the student edition version of LabVIEW 2019 software [21]. This program is the backbone of the data acquisition and analysis process, empowering researchers with the flexibility to tailor and control the entire testing procedure to suit their specific experimental requirements. The vibration program developed in LabVIEW 2019 software provides researchers with a powerful and intuitive platform for designing and executing suspension testing experiments. Its user-friendly interface allows researchers to easily configure and customize various parameters, such as vibration frequencies, amplitudes, durations, sampling rate, and data acquisition intervals.

The LabVIEW-based vibration program also offers advanced data analysis tools, allowing researchers to comprehensively process and interpret the collected vibration data. Researchers can perform various analyses, such as Fast Fourier Transform (FFT) analysis, time-domain analysis, and statistical analysis, to gain deeper insights into the suspension system's behavior and response to different vibration inputs. Furthermore, the program's data logging capabilities facilitate storing and retrieving large volumes of experimental data. This logging feature ensures that researchers have access to a comprehensive dataset for subsequent analysis, cross-referencing, and comparison, providing a solid foundation for drawing meaningful conclusions and making data-driven decisions.

4. 4. Taguchi method and analysis of variance

According to [10], the Taguchi method offers various advantages. One advantage is that accommodating multiple factors and quantities enables more efficient experimental design. Additionally, it allows for developing a process that consistently produces robust products, even in the presence of uncontrollable factors. Furthermore, it provides insights into the impact of different factors and the optimal values of control factors.

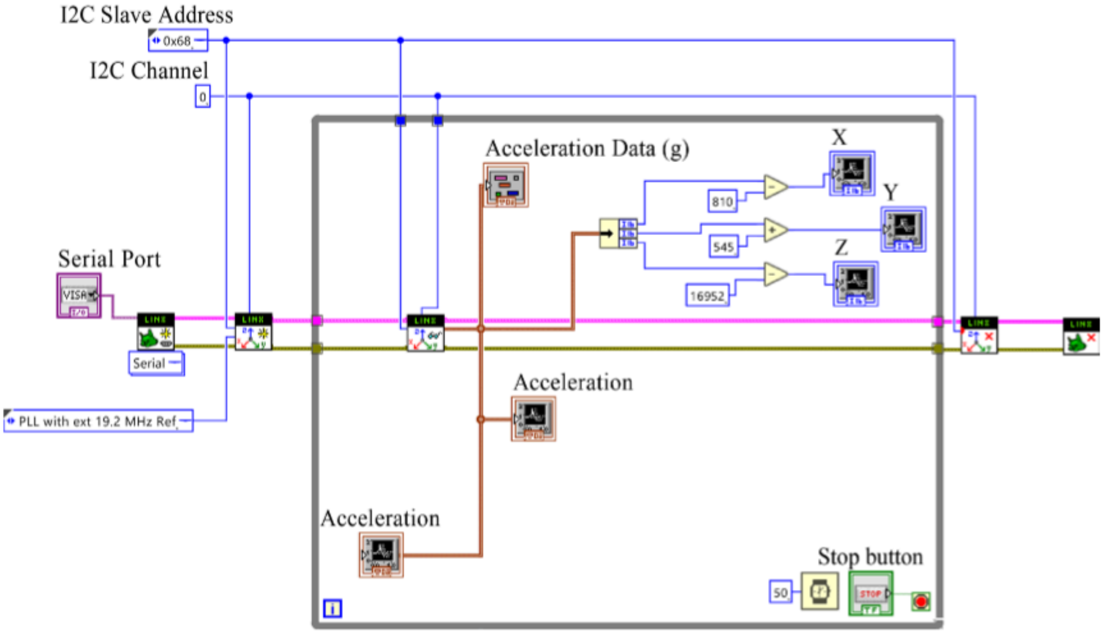


Fig. 5. Vibration program using LabVIEW 2019 version student software

In this case, *L* represents the total number of possible combinations between the number of experiments (*a*), the number of levels (*b*), and the number of variables (*c*). For what is known as multiple-factor trials, the S/N ratio was created using the Taguchi method. Researchers can always choose the highest-level factor value to maximize the quality attributes of the experiment because of the way the S/N ratio is defined. The signal-to-noise ratio (S/N ratio) is used to lessen noise's impact on quality metrics. The outcomes of quality-related procedures are quality attributes. The lower the S/N ratio employed, the better it was for this investigation. The higher the performance, the lower the S/N ratio [22].

Analysis of Variance (ANOVA) is a valuable tool in the Taguchi method as it allows for the statistical analysis and interpretation of experimental data. The data type that can be analyzed is measurement results, which can be analyzed using Analysis of Variance for Variable Data. The confidence interval (CI) represents a range of values within which the true average value is expected to fall with a certain confidence level. It is determined by calculating the maximum and minimum values encompassing the desired confidence percentage. The confidence interval for the predicted mean is calculated using the formula provided in reference [23].

Data processing in this study was conducted using Taguchi's experimental design as the primary tool, continuing until the experiments yielded confirmatory results to identify the factors that significantly affected the suspension system's performance. The Taguchi method is a powerful statistical technique that enables researchers to efficiently explore a wide range of factors and their interactions, facilitating the identification of the optimal level settings for improved suspension behavior. Through the Taguchi method, researchers could systematically assess the impact of various factors on the suspension system's response to vibration inputs. These factors could include suspension geometry parameters, spring rates, damping coefficients, tire pressure, and other relevant variables influencing ride comfort and handling characteristics. Table 1 presents a comprehensive visual depiction illustrating the meticulously established level settings for each parameter under investigation. The table below provides a complete representation of the precise numerical values or designated ranges carefully selected to encompass the full spectrum of significant factors inherent in the suspension system. Acknowledging that these specified levels function as distinct configurations independent of the experimental trials is imperative. The employed tactical strategy enables researchers to systematically examine how individual modifications impact the suspension system's dynamic response to vibrations. This experimental setup aims to enhance the suspension system of Altis cars, a popular type of sedan extensively utilized in Indonesia. The tire size used for this research is 205/55 R16.

Table 1

Determination of factors and Number of Level Values

No.	Control factors	Unit	Level		
			1	2	3
1	Mound height (*A*)	Cm	5	10	15
2	Tire pressure (*B*)	Psi	28	30	32
3	Passenger weight (*C*)	Kg	56	84	112
4	Dynamic load (*D*)	Kg	71	141	212

Combining the Taguchi method and the empirical data in Table 1 significantly enhances analytical capabilities. The integration of this platform offers an opportunity to gain deep insights into the field of suspension system optimization. By identifying the key factors that significantly impact the system's complex behavior and determining the ideal settings for these factors, researchers gain the necessary knowledge and tools to make informed decisions. The user's text highlights the impact of newfound comprehension on the iterative evolution of suspension design. This comprehension serves as a catalyst, driving the design process toward achieving predefined performance benchmarks.

5. Results of Experimental Design on Suspension Test Equipment

5. 1. Research Design Results

The research design employed in this study was an orthogonal matrix L9 (34) with three replications, ensuring a well-structured and efficient experimental setup. The use of an orthogonal matrix allowed for the systematic variation of factors and levels, reducing potential bias and facilitating a comprehensive investigation of the suspension system's response to different conditions. The researchers employed a data retrieval process based on amplitude values to gather vibration data, a critical aspect of understanding the system's dynamic behavior. The use of FFT graphs [24] facilitated the analysis of frequency components present in the vibration data, providing a detailed view of the system's responses across different frequencies.

Table 2 presents the collected measurement results, providing a comprehensive record of the experimental outcomes. This table likely includes the recorded vibration amplitudes corresponding to each factor level combination and replication. The data retrieved from the measurements offers valuable insights into the suspension system's performance under various experimental conditions.

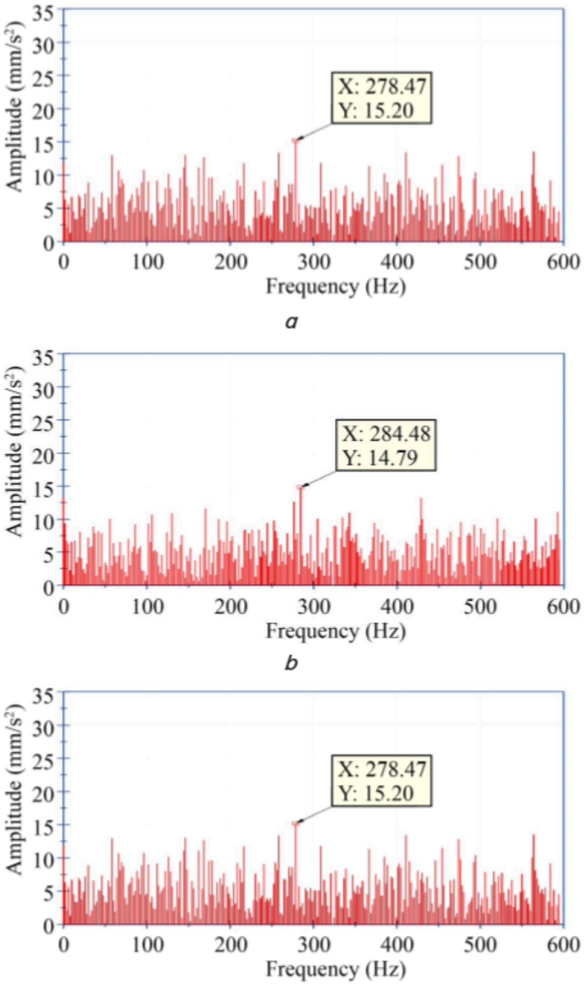
Table 2

Data retrieval of measurement results

Exp	Factor				Suspension Vibration Rating RMS FFT (mm/s^2)			
	A	*B*	*C*	*D*	I	II	III	Mean
1	5	28	56	71	15.20	14.79	15.82	15.27
2	5	30	84	114	25.94	25.44	26.44	25.94
3	5	32	112	212	30.21	30.31	29.33	29.95
4	10	28	84	212	37.67	36.96	38.15	37.59
5	10	30	112	71	21.55	23.94	24.41	23.30
6	10	32	56	114	33.76	34.41	34.69	34.28
7	15	28	112	114	43.96	44.16	42.89	43.67
8	15	30	56	212	58.22	58.48	60.53	59.07
9	15	32	84	71	29.19	31.90	31.23	30.77

The experimental conditions yielded an average suspension vibration value of 33.31 mm/s^2. This measured value provides a crucial benchmark for evaluating the performance of the suspension system under specific test conditions. By comparing this average vibration value with other experimental setups or standard references, researchers can assess the effectiveness of the suspension system in dampening vibrations and providing a smooth ride experience. Additionally, it allows for a quantitative comparison of the system's performance against desired targets or industry standards.

The results of retrieving the vibration data from the suspension portion are shown in Fig. 6. The MPU6050 sensor was used to capture the amplitude acceleration data. This data was afterward translated into FFT signals to analyze the frequency components.



a

b

c

Fig. 6. Suspension vibration data retrieval in the form of Fast Fourier Transform signals: *a* — replication I; *b* — replication II; *c* — replication III

During Experiment 1, three replications were conducted to assess the amplitude of vibrations in the suspension system. The measured vibration amplitude in the first replication (Fig. 6, *a*) was 15.20 mm/s^2. Subsequently, in the second replication (Fig. 6, *b*), the amplitude reduced slightly to 14.79 mm/s^2. The highest vibration amplitude value, 15.82 mm/s^2, was recorded during the third replication (Fig. 6, *c*). These varying results across the repetitions highlight the importance of conducting multiple trials to account for experimental variations and ensure reliable data collection. The slight variations in vibration amplitudes between replications demonstrate the dynamic nature of the suspension system's behavior and its sensitivity to various factors.

5. 2. Optimization using the Taguchi Method and Analysis of Variance

The evaluation of the S/N ratio is an essential component of this study because it enables the analysis of the quality attributes of each response in the suspension test equipment. In this study, the vibration response is evaluated based on the criterion of «the smaller, the better». Lower vibration values are generally preferred and seen as a sign of better performance in the suspension system. The S/N ratio is calculated for each experimental run to evaluate the effectiveness of different combinations. The ratio mentioned here is a numerical measure used to assess the signal-to-noise ratio. In this context, the signal refers to the desired response, which smaller vibration values indicate.

On the other hand, the noise represents the variability or deviation from the desired response. Table 3 displays the vibration values obtained from the suspension test equipment for the second and ninth combinations. The values provided comprehensively analyze the system's behavior by recording vibration responses under specific experimental conditions.

Table 3

Response table for suspension vibration

Level	Embankment height (cm)	Tire pressure (psi)	Passenger weight (kg)	Dynamic load (kg)
1	−27.16	−30.33	−29.94	−26.94
2	−29.86	−30.36	−29.85	−30.60
3	−32.67	−30.00	−29.90	−32.15
Delta	−5.50	−0,03	−0.09	−5.22
Rank	1	3	4	2

Fig. 7 illustrates the ideal levels for each component, corresponding to the combinations resulting in the lowest values. It is worth noting that Factor *A* (Embankment height) has been classified as Level 1, while Factor *B* (Tire pressure) has been designated as Level 3, and Factor *C* (Passenger weight) has been seen to be at Level 2. Ultimately, it has been shown that Factor *D* (Dynamic load) exhibits the highest level of efficacy at Level 1. Identifying and implementing ideal level combinations play a crucial role in attaining optimal performance results for the suspension system. By selecting the minimum values for each element, researchers can discern the configurations that effectively reduce vibration levels, improve ride comfort, and maximize the overall performance of the suspension system.

Fig. 7 provides valuable insights into the optimal values for each parameter. The ideal configuration suggests an embankment height of 5 cm, which strikes the right balance between road clearance and stability, ensuring efficient absorption of road irregularities and minimizing vibrations. The recommended tire pressure of 32 Psi contributes to optimal tire performance, enhancing traction and fuel efficiency while maintaining overall ride comfort. The specified passenger weight of 84 kg also ensures that the suspension system can comfortably accommodate typical occupant weights, promoting a smooth and enjoyable ride experience. Lastly, the dynamic load of 71 kg, identified as the optimal value, underscores the importance of managing varying loads during different driving conditions. By calibrating the suspension to handle this dynamic load effectively, the vehicle can maintain stability, superior handling, and exceptional ride quality, even on challenging road surfaces.

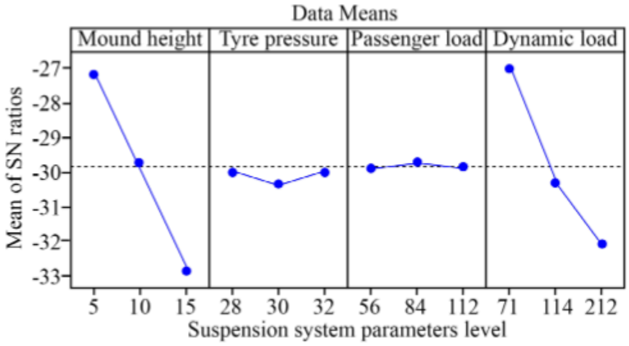


Fig. 7. Main Effects Plot of S/N Ratio on the Vibration value Acceleration RMS Suspension

Analysis of Variance (ANOVA) is a statistical method employed to examine the relationship between control parameters and quality characteristics in the context of the carburizing process of carbon steel under tension. This analysis helps determine the degree of contribution each control parameter has on the quality characteristics of the treated steel. The ANOVA results provide valuable insights into the significance of each control parameter in influencing the outcome of the carburizing process. By quantifying the contribution of each parameter, engineers and researchers can prioritize and optimize the most influential factors to achieve desired material properties.

The statistical analysis using ANOVA regression is conducted within the framework of the Taguchi method, utilizing an orthogonal array L9 to design and conduct the experiments [17] efficiently. This enables researchers to explore various combinations of control parameters in a systematic and organized manner, ensuring comprehensive coverage of the parameter space. During the ANOVA regression analysis, if the obtained p-value is less than 0.05, it indicates a statistically significant relationship between the control parameters and the quality characteristics of the carburized carbon steel [9, 25]. In such cases, the ANOVA regression results are considered valid and reliable, offering valuable information on the impact of the control parameters on the carburizing process. The calculation results of the ANOVA S/N Ratio are presented in Table 5, providing a comprehensive summary of the statistical outcomes. These results offer a clear understanding of the relative contributions of each control parameter to the surface hardening characteristics of the carbon steel under tension.

Table 5

Analysis of variance analysis for suspension vibration

Source	DF	Sum of square	Mean of square	F-value	p-value	Persentage contribution
Embankment height (cm)	1	45.4527	45.4527	19.94	0.011	56.096
Tire pressure (psi)	1	0.6761	0.6761	0.30	0.615	0.834
Passenger weight (kg)	1	0.0024	0.0024	0.00	0.976	0.003
Dynamic load (kg)	1	34.8965	34.8965	15.31	0.017	43.067
Error	4	9.1168	2.2792	–	–	–
Total	8	90.1445	–	–	–	–

This study used the significance of the control parameters according to the confidence level of 95 % and the p-value of 0.05. The calculated F value (F-Test) is the ratio mean square error against residues and is used to determine the significance of control factors. The F-test result calculated from the control factor is $F(0.05)=7.70$. Based on the results of ANOVA calculations for the mean value and the value of the S/N ratio. Based on the contribution rate of the result, $F_{count} \geq F_{table}$ is factor *A* (Embankment height) and factor *D* (Dynamic load) influencing factors, while factor *B* and Factor *C* are factors that have no effect or are not significant.

The study's findings revealed that the parameter with the most significant contribution to suspension vibration is embankment height, accounting for an impressive 56 % of the overall impact. Embankment height is crucial in determining the suspension system's behavior, directly affecting the vehicle's ability to absorb road irregularities and provide a smooth ride. Following closely behind, the dynamic load exerts a notable influence on suspension vibration, contributing approximately 43 % to the overall effect. The dynamic load refers to the varying weight and forces experienced by the suspension system as the vehicle travels over different road conditions. Managing the dynamic load is essential for maintaining vehicle stability and ride comfort.

In contrast, the tire pressure's impact on suspension vibration was relatively negligible, contributing less than 0.1 %. While tire pressure is vital for optimal tire performance and fuel efficiency, its influence on suspension vibration in this study appears minimal. Similarly, the passenger weight's effect on suspension vibration was even less significant, contributing less than 0.01 %. While passenger weight does affect the overall load on the suspension system, its contribution to suspension vibration is comparatively minor in this specific context.

6. Discussion of the Results of Optimization of Suspension Testing Equipment Using the Taguchi Method and Analysis of Variance

The vibration amplitude was 15.20 mm/s^2 on the first try at repeating Experiment 1 (Fig. 6, *a*). This number shows the movement or oscillation experienced by the vehicle's suspension due to external forces acting on the car while it is in motion. The initial replication's recorded amplitude is useful information on the vibration level experienced. The vibration amplitude was measured to be 14.79 mm/s^2 in Replication 2 of Experiment 1, as shown in Fig. 6, *b*. Compared to the original, this number suggests that the amplitude of the vibrations is somewhat reduced. Differences in amplitude values across replicates provide evidence for the potential effect of random variables or noise on experimental outcomes.

The vibration amplitude value of 15.82 mm/s^2, which is the highest recorded, was observed in the third replication of Experiment 1 (Fig. 6, *c*). The value provided indicates the highest vibrations recorded during this replication. Based on the findings of the third replication, it can be inferred that the suspension system exhibited the highest degree of oscillation or vibration.

The observed differences in vibration amplitude values across replications highlight the significance of conducting multiple replications in experimental studies. Replication is a valuable practice that allows for the consideration of uncertainties and random factors that could impact the results. It also enables a thorough evaluation of the system's behavior across various conditions, leading to a more comprehensive assessment.

Factor *A*, which represents the height of the mound, has been determined to be at Level 1. The optimal level for the suspension system's performance is at this level. This suggests that a lower embankment height is beneficial in reducing vibration levels and enhancing ride comfort. The user states that Factor *B*, which represents tire pressure, is classified as Level 3. The data implies a correlation between higher tire pressure and better suspension performance. This correlation could potentially lead to improved handling and stability of the vehicle while driving [26, 27].

The variable *C* represents the passenger weight and is observed at Level 2. The passenger weight at this level is chosen to minimize vibrations and improve comfort for vehicle occupants. Factor *D*, which represents dynamic load, demonstrates the highest level of effectiveness at Level 1. The data suggest that a decrease in dynamic load is the most efficient approach for minimizing vibration levels and optimizing the performance of the suspension system.

Identifying and implementing ideal-level combinations is critical in achieving optimal results for the suspension system. Researchers can analyze the data by choosing the minimum values for each element. This allows them to determine which configurations are most effective in reducing vibration and enhancing ride comfort. Understanding this information enables the precise adjustment of the suspension system, resulting in an elevated driving experience, increased vehicle stability, and improved overall performance.

According to the analysis results, the height of the mound was the factor that had the most significant impact on suspension vibration. This factor was responsible for 56 % of the total effect. It was revealed that dynamic loads had a considerable impact, accounting for approximately 43 % of the total influence of suspension vibration in the vehicle. The effect of tire pressure on suspension vibration is negligible, accounting for less than 0.1 % of the total impact. The result of passenger weight on suspension vibration is relatively minimal; it contributes less than 0.01 % to the overall effect. Although it is well known that the weight of the passengers affects the load carried by the suspension system, the contribution that passenger weight makes to the phenomenon of suspension vibration is generally considered minor. The performance of the suspension system is greatly affected by various parameters, including the height of the embankment and the dynamic loads.

The study's findings support the common belief that the height of road irregularities, such as embankments, notably impacts suspension behavior and vehicle vibrations. More significant road deviations are expected to result in more noticeable vibrations, which can negatively affect both ride comfort and the overall passenger experience. It is worth mentioning that the findings of this study are consistent with general expectations. However, the quantitative analysis conducted in this research provides detailed insights into the magnitude of the effect. Additionally, this study examines how factors such as tire pressure and passenger weight interact with road irregularities to impact suspension performance. The findings have significant value in optimizing suspension systems. They offer a comprehensive understanding of the combined impact of various factors on ride comfort and vehicle stability.

The potential limitation of this study is that the simulation of road conditions may not accurately represent the intricate and varied nature of actual road surfaces in the real world. The variability of road irregularities is significant, and it is essential to note that the selected road profiles may not account for all potential scenarios. The study utilizes predetermined road surface parameters to conduct simulations. The parameters used in this study may not accurately reflect the actual features of real roads, which could potentially restrict the applicability of the findings to real-world situations. The study's assumption of a constant passenger weight fails to account for the variability in passenger loads observed in real-world scenarios. The impact of varying passenger weights on suspension behavior is not adequately accounted for. The research's focus on a particular vehicle model or suspension type restricts the applicability of the findings to other vehicle models with different suspension designs.

One of the disadvantages of this study is the utilization of a simplified model for the suspension system, which overlooks the intricate interactions in real-world scenarios. The simplification may not comprehensively represent the complexities of actual suspension behavior. Furthermore, it is essential to consider how environmental conditions, such as temperature and humidity, can affect the performance of suspensions. The study frequently overlooks these factors, which could result in findings not applicable in different circumstances. The Taguchi method assumes that there are linear relationships between factors and responses. Suspension systems commonly display non-linear behaviors caused by friction, stiffness variations, and dynamic forces. The linear assumption may not accurately capture the complexity of the real system.

One potential solution to this disadvantage is to conduct additional research that examines explicitly advanced modeling techniques. The techniques should focus on accurately representing the suspension system's intricate dynamics and non-linear properties. Future research could include implementing field tests to validate optimized parameters in real-world driving conditions. Future research has the potential to explore the integration of advanced mechanisms capable of generating dynamic loads. The mechanics may involve road simulations or real-world driving tests. Future research has the potential to explore the integration of multi-objective optimization approaches as a means to handle and harmonize various performance metrics efficiently.

Future research has the potential to investigate various avenues to advance the field of vehicle suspension optimization. Integrating artificial intelligence (AI) and machine learning (ML) techniques is a fascinating area of research. The goal is to develop suspension control algorithms that are highly adaptable and intelligent. The algorithms are intended to quickly adapt to changes in road conditions and drivers' preferences. This would result in an intelligent suspension system that improves performance, safety, comfort, and the overall driving experience. Researchers can use AI and ML to develop suspension systems that can adapt to real-time data inputs, predict road irregularities, and adjust damping and stiffness parameters automatically. This enables the suspension system to balance vehicle stability and passenger comfort harmoniously. The emerging integration of vehicle dynamics and advanced AI can significantly transform how vehicles interact with the road. This collaboration could redefine the standards for ride quality, handling precision, and overall driving experience.

The research is limited in terms of its scope. The research appears to have primarily concentrated on enhancing the suspension test equipment by applying the Taguchi method. However, the study may have overlooked the wider perspective of the complete vehicle suspension system. Although optimizing test equipment is important for conducting controlled experiments, it may not necessarily result in direct improvements in vehicle suspension performance in real-world scenarios. One potential limitation of the Taguchi method is its applicability to all potential variations of suspension systems. The complexity and variability of suspension designs may influence the effectiveness of the Taguchi method as an optimization technique. The study's findings may be limited due to the specific configuration and characteristics of the suspension test equipment. Further validation and adjustments may be necessary to apply these findings to other types of suspension systems.

7. Conclusions

1. The study conclusively achieved significant milestones in enhancing car suspension system performance by optimizing value conditions. The specified circumstances are as follows: the embankment height is 5 cm, the tire pressure is 32 Psi, the passenger weight is 84 kg, and the dynamic load is 71 kg. In conclusion, these customized settings effectively absorb road disturbances, maintain stability, and reduce vibrations, resulting in a harmonious equilibrium.

2. The results from the analysis of variance show how the various factors had diverse impacts on the research. Factor A, the height of the mound, has a 56 % bearing on the success with which road irregularities are dealt with and the steadiness with which the vehicle is driven. Regarding keeping your vehicle stable and your ride quality high regardless of conditions, 43 % of the puzzle is solved by the dynamic load (factor D). In contrast, parameters B (tire pressure) and C (passenger weight) have negligible influence, less than 0.1 %, on suspension vibration at this setting, although continuing to be important for overall vehicle performance and safety.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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