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Experimental Study on Railway Vehicle Lateral Performance under Different Lateral Disturbance

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ABSTRACT

Railway systems are integral to modern transportation, connecting regions and facilitating the movement of goods and passengers. One critical aspect of railway performance is the lateral dynamics, influenced by various external disturbances. In this study, an experiment was carried out to investigate the lateral performance of railway vehicles subjected to different lateral disturbances. The research utilizes an experimental approach and analytical tools to comprehensively analyze the effects of lateral disturbances on railway performance. The double-acting pneumatic actuator was used which acts as lateral disturbance with the five different pressures. Then, the accelerometer sensor was used to record the motion of the railway vehicle including track, bogie, and body, and the data was analyzed in MATLAB software. The primary objectives are to quantify the dynamic responses of railway vehicles under these disturbances and assess the impact on lateral acceleration. Comprehensive data analysis provides insights into the behaviors of railway vehicles in real-world scenarios. Results from this study show high force lateral disturbances can trigger dynamic responses in the train system. This may include swaying, hunting oscillations, or wheel unloading, all of which can affect the overall performance and stability of the train. The lateral acceleration increases when the lateral disturbance increases. Therefore, disturbance contributes to a deeper understanding of lateral dynamics in railway systems, aiding in the development of robust control systems.

1. Introduction

The study of railway vehicle dynamics is an intriguing subject that offers a practical application of nonlinear dynamical systems theory. Railway vehicles are analyzed to gain insights into their nonlinear characteristics, primarily arising from factors such as the kinematic relationship between wheels and rails, the stress distribution on the wheel/rail contact surface, and constraints on motion that result in impact forces [1].

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In other hand, the railway sector is diligently striving to refine design and technology to enhance the safety, efficiency, and comfort of rail transportation [2]. According to Bruni *et al.,* [3] the dynamics of railway vehicles can be ride comfort, safety, and the overall performance of the railway system. However, the concept of lateral dynamics is closely associated with the unique geometry of wheels and rails, as well as the conicity of the wheels and how rail vehicles achieve control and lastly, the longitudinal dynamic relates to the forward and backward motion of the railway vehicle [4]. These dynamics are significant for achieving smooth acceleration and deceleration, as well as ensuring that the train maintains a safe and stable speed profile. Various interesting phenomena, such as the presence of stationary motions, periodic motions, chaotic motions, and quasi-periodic motions and the intriguing transitions between these states, may develop in the nonlinear dynamical systems of a railway car [5]. In his research, Hashim *et al.,*[6] stated that the Gauge-Chage Technology (GCT) is needed to control the wheel gauge to provide better train wheel movement. It also involves investigating how trains navigate curves, accelerate, brake, and handle various operating conditions [7]. However, excessive motion especially lateral will lead to unwanted vibrations like hunting and swaying which cause motion sickness and discomfort [8]. Thus, understanding railway dynamics is crucial for designing efficient and safe rail systems, optimizing energy consumption, and ensuring passenger comfort.

Moreover, the issue of hunting stability holds paramount importance within the dynamic systems of railway vehicles. In this context, “hunting” denotes the dynamic interplay between two degrees of freedom, namely lateral and yaw, wherein the behavior of a wheelset exhibits instability. The occurrence of hunting is frequently observed when railway vehicles are in motion at high velocities. The small-amplitude hunting, however, not only affects ride comfort but also aggravates the wheel–rail wear [9,10]. Cooperrider [11] analyzed the hunting behavior of conventional trucks and determined the impacts of flange contact, wheel slip, and Coulomb friction on vehicle stability. The amplitude and frequency of the hunting phenomenon escalate as the vehicle speed rises, in conjunction with changes in the wheel and rail equivalent conicity resulting from the alignment of wheel and rail profiles [12]. In addition, when a rail vehicle encounters crosswinds, it responds by exhibiting a swaying motion of the car body. These oscillations have the potential to drastically damage the dynamic performance of the vehicle system or, in the worst-case scenario, cause derailment [13]. Besides, the cost of track maintenance can be high due to the significant levels of vibration experienced within the rail track system [14]. Thus, the installation of dampers in the lateral direction within the secondary suspensions is necessary for effectively suppressing the vibrations. This is because secondary lateral damping plays a pivotal role in achieving optimal vibration suppression [15]. The lateral suspension systems help in minimizing the lateral vibration, which contributes to the swaying phenomenon on the railway car body, and provides stability to the vehicles.

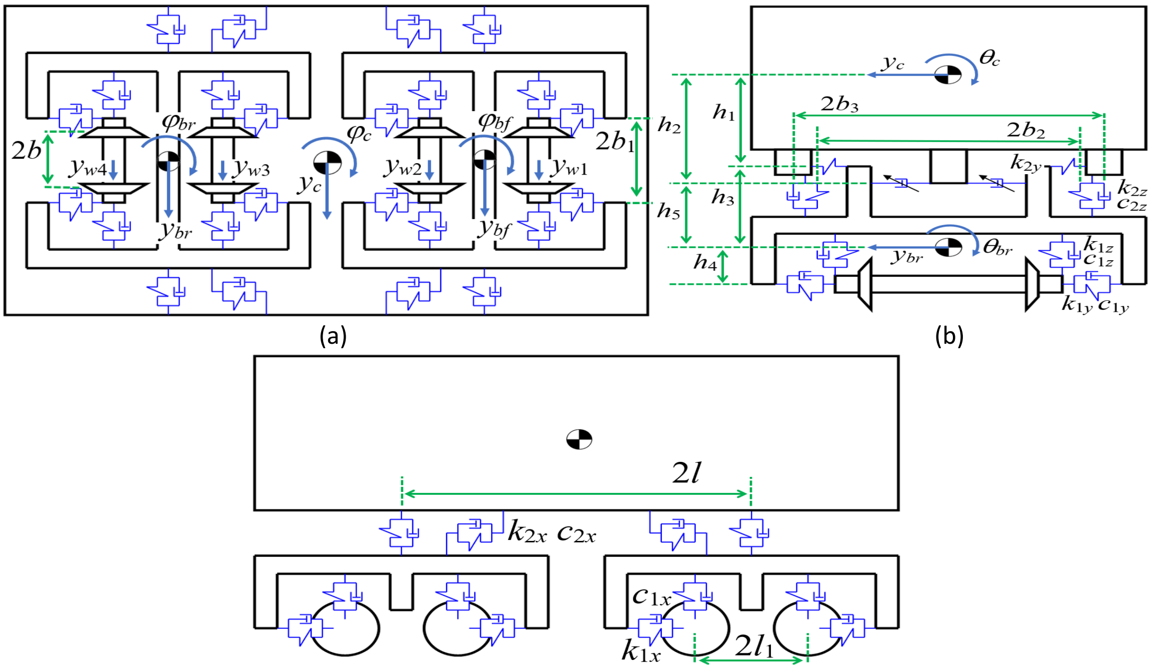
Furthermore, the evaluation of a rail vehicle's performance is determined through measurable assessments of both its ride quality and stability. The concept of stability in railway vehicle dynamics research and development is not a recent one. Extensive efforts have been dedicated to enhancing stability and ride comfort in this field [16]. Stability had a strong relationship with ride comfort. Ride comfort, on the other hand, concerns the passenger experience, focusing on minimizing vibrations, jolts, and lateral movements during the journey. Increasing stability can frequently result in a reduction in ride comfort, as overly stiff suspensions or control systems geared for stability may send more vibrations to the passengers [17]. The consideration of ride comfort is an important factor in the analysis of the dynamics of railway vehicles, as it plays a critical part in the modeling and assessment of vibration characteristics. In practical application, it is important to possess a means of assessing the level of ride comfort to ascertain the ability of the railway vehicle to meet the fundamental demands of passenger services [18]. Passengers prefer a smooth and comfortable ride, free from excessive shaking or swaying. Thus, lateral disturbances, such as sudden lateral movements or swaying, can greatly impact the comfort of passengers on a train or the stability of the train itself. These disturbances disrupt the smoothness of the ride, making it less enjoyable and potentially causing discomfort or nausea [19].

In this study, the experiment was conducted in the laboratory using a railway-scaled model. The effect of various lateral disturbances on the car body, bogie, and track was studied and analyzed. While numerous studies have been conducted on vehicle dynamics in general or specific features such as vertical performance, this present research specifically investigates the lateral performance of vehicles in response to varied lateral disturbances. Thus, it provides a nuanced understanding of how different lateral forces, such as wind or track irregularities, affect railway vehicle stability and safety.

2. Methodology

2.1 Railway Analytical Model

Figure 1 shows the arrangement of the railway vehicle with its suspensions. The illustrated train model comprises a single car body, two bogies, and a total of four wheelsets. Secondary suspensions connect the car body to both the front and rear bogies, while primary suspensions link each bogie to two wheelsets. The dampers are positioned within the lateral secondary suspensions as lateral damping in the secondary suspension is considered the most crucial factor for mitigating vibrations in the car body [20].



(a) (b)

(c)

Fig. 1. Schematic diagram of a railway vehicle (a) Top View (b) Front View (c) Side View [21]

2.2 Experimental Setup and Measurement Configuration

When external sources generate vibrations in the car body, there is a sudden change of lateral vibration parameters which causes violent swinging of the railway vehicle body called the swaying phenomenon[22] . This study primarily concentrates on measuring the car body's lateral and yawing accelerations and a railway-scaled model was used to run the test shown in Figure 2. Hence, to observe the general situation of the lateral vibration on the track, bogie, and body, the lateral and yawing accelerations are logged and analysed. The test equipment was installed as shown in Figure 4. Five distinct pressure levels 2 bars,3 bars, 4 bars, 5 bars, and 6 bars were applied during the experiment. In addition, Figure 3 shows other equipment required for this experiment like an air compressor, two push-button spring return valves, and a regulator. The pneumatic actuator generated lateral disturbances, and the resulting acceleration was quantified using a smartphone application called the ‘Accelerometer Meter’ as shown in Figure 6. These smartphone innovations enable users to engage in activities beyond mere communication[23]. Other than that, the Internet of Things (IoT) also has a high potential to accelerate the people daily routine and work-life [24].An accelerometer sensor is a device that is used to measure acceleration forces in various directions. It is commonly found in many electronic devices and systems to detect and quantify changes in velocity, tilt, vibration, and shock. Figure 5 shows the location of the accelerometer and it was placed firmly on the track, bogie, and body to measure the motion of the railway vehicle during the experiment. The effectiveness of the reading depends on the movement of the object due to the sensitivity of the accelerometer sensor. The dynamic responses of the railway car body, bogie, and track can be measured for different lateral disturbances by changing the pressure through the regulator.

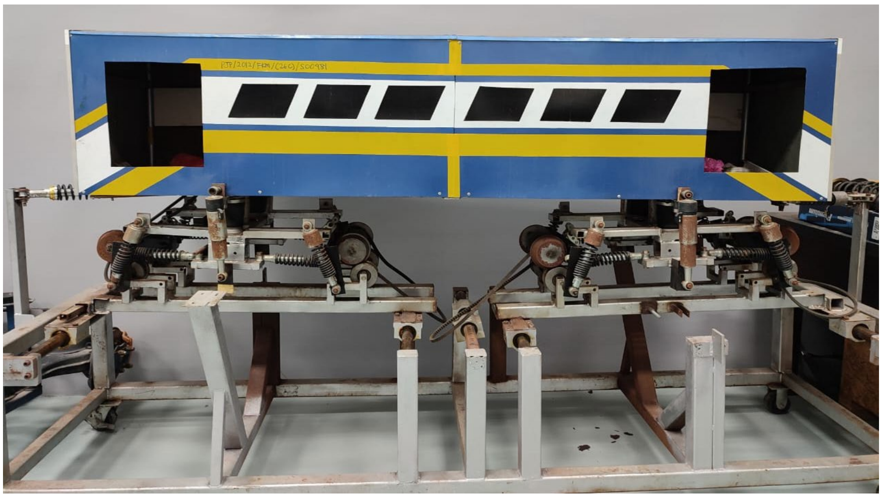


Fig. 2. Railway scaled model

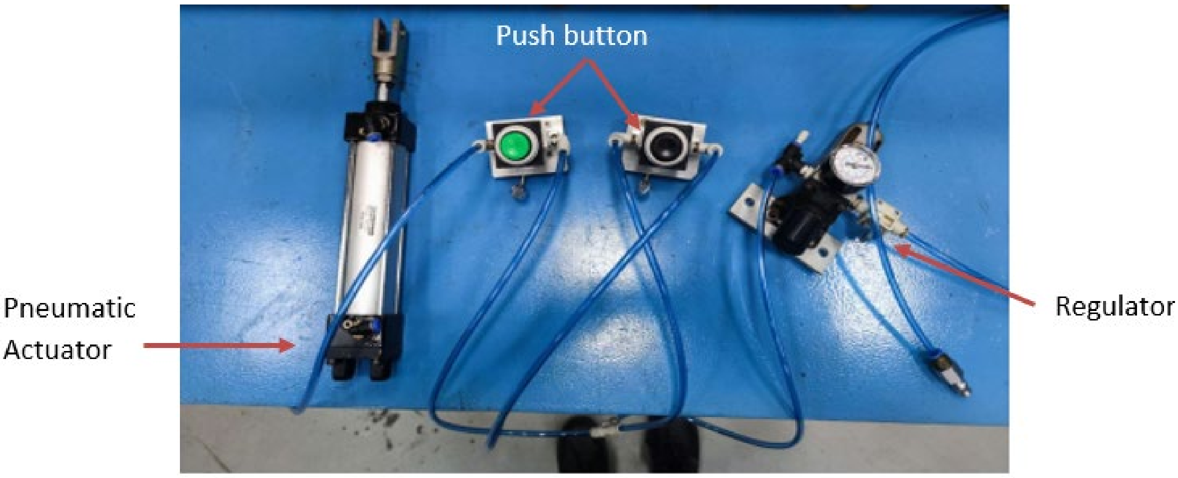


Fig. 3. Equipment for lateral disturbance testing

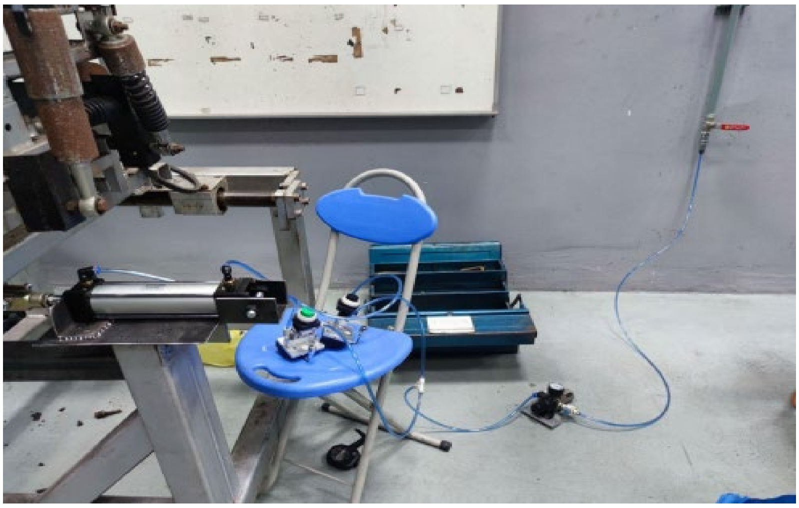
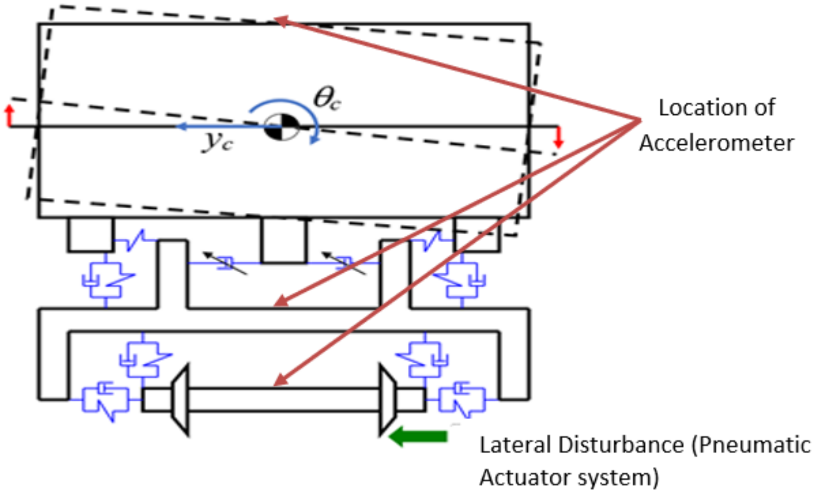


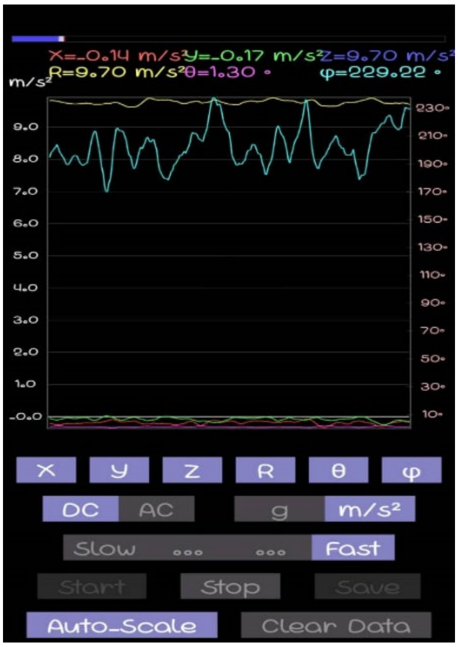
Fig. 4. Equipment Installation for testing purposed



Location of Accelerometer

Lateral Disturbance (Pneumatic Actuator system)

Fig. 5. Illustrated model of lateral disturbance on track



X=-0.14 m/s² Y=-0.17 m/s² Z=9.70 m/s²
R=9.70 m/s² θ=1.30 ° φ=229.22 °

Fig. 6. Accelerometer Application Appearance

2.3 Pneumatic Actuator System

A double-acting pneumatic actuator had been used in this experiment as a lateral disturbance. The pneumatic actuator helps to control the movement of various mechanical components, such as valves, dampers, and other mechanisms. It operates by using compressed air to generate linear or rotary motion in both directions (extending and retracting) for performing mechanical work. Figure 7 shows the schematic of a double-acting pneumatic actuator with two push-button spring valves. The force and speed of movement of a double-acting pneumatic actuator are affected by parameters such as air pressure, actuator size, and load. These actuators can generate significant force and deliver quick motion when needed.

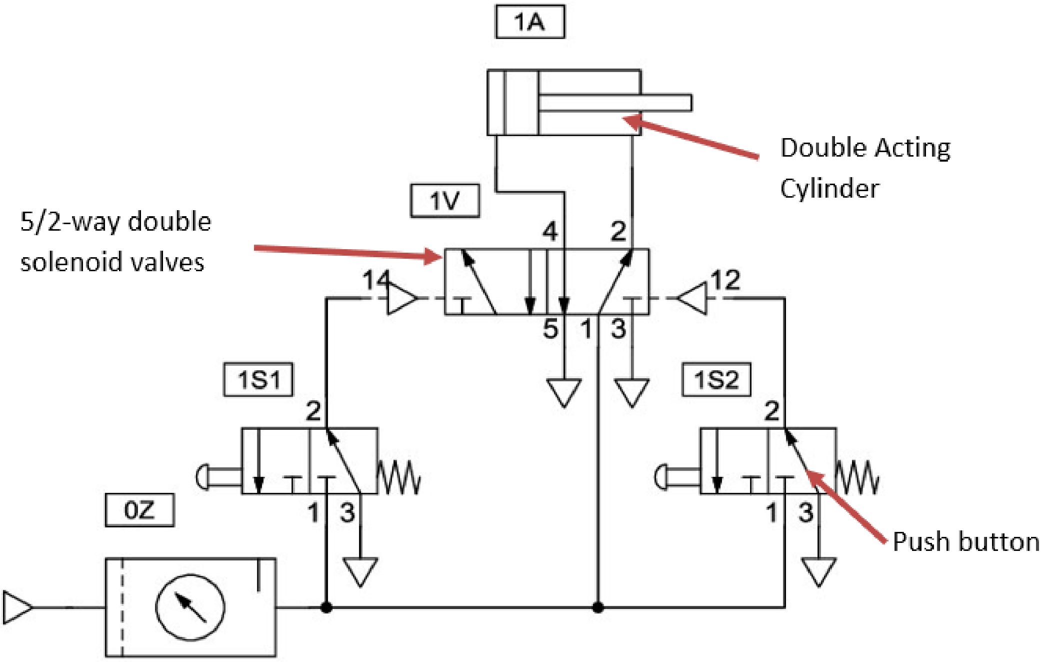


Fig. 7. Indirect control system with a double-acting cylinder

Figure 7 shows indirect system with a double-acting cylinder. The cylinder 1A is extended when the 1S1 3/2 valve (3-way 2 positions) button is pressed. As a result, the valve opens in ways 1-2 and closes in ways 3 and 4. In this case, the 1S1 valve transmits a control signal 14 to 1V 5/2 valve (5-way 2 positions), opening and closing ways 1-4 and 2-3. After manually actuating the 1S2 valve, which results in the generation of control signal 12 to the 1V valve, the cylinder is retracted. The flow chart of the experimental process is shown in Figure 8.

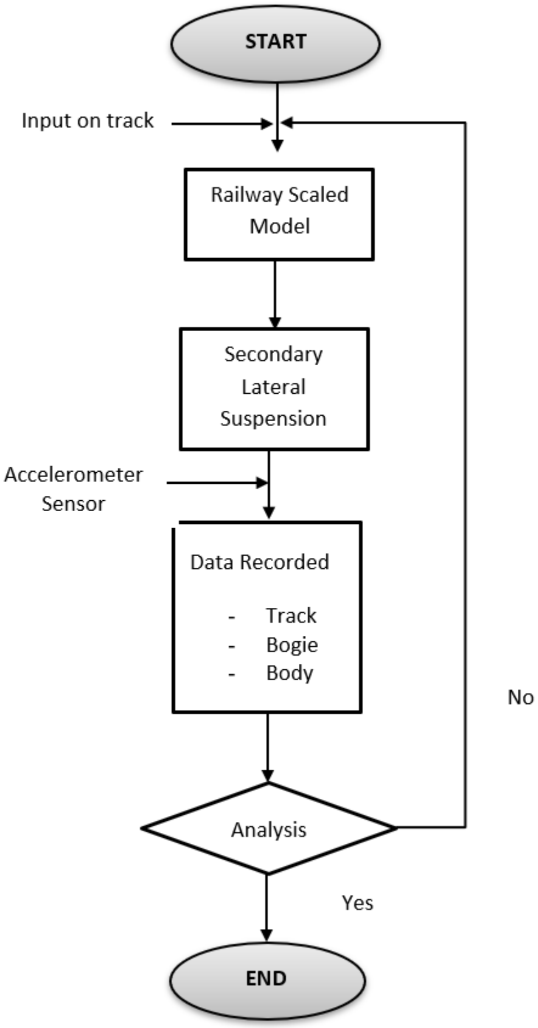


Fig. 8. Flowchart of experimental process

3. Results and discussion

The performance of a railway vehicle is intricately tied to its lateral dynamics, which are greatly affected by various lateral disturbances encountered on the track. These disturbances encompass a spectrum of factors, each influencing the vehicle's behavior and stability. The purpose of this experiment was to evaluate the acceleration over time for lateral disturbances using a pneumatic actuator. In this experiment, the secondary lateral damping coefficient C_{2y} = 1.8 x 10^4 Ns/m is used as a fixed parameter. Figure 9 shows the higher pressure of 6 bars acting as a lateral disturbance gave a high amplitude of body lateral acceleration with a maximum value of 6.872 m/s^2 and the lowest value of 0.9732 m/s^2 at a lower pressure of 2 bars in the time range of 10 s. When the pressure increases from 2 bars to 6 bars, the peak value of car body accelerations in the lateral increase because when the speed of lateral disturbance increases, the lateral acceleration experienced by the railway vehicle's body will also increase. This is because the vehicle needs to exert greater lateral forces to maintain stability and counteract the disturbance. Moreover, higher lateral acceleration can also lead to reduced ride comfort for passengers. Passengers may feel more lateral sway and discomfort as the vehicle responds to the disturbance with increased acceleration. Moreover, the value of yaw acceleration on the car body as recorded in Figure 10 shows a high peak value of 6.122 rad/s^2 at high pressure of 5 bars and the maximum value for low pressure at 2 bars was 1.274 rad/s^2. The high-pressure lateral disturbances can induce more significant yaw motion in the railway vehicle's body. The body of the railway vehicle may experience yawing as it encounters lateral forces from disturbances like crosswinds, track irregularities, or sharp curves at higher pressure. Excessive yaw motion can lead to discomfort for passengers and pose stability challenges for the train operator.

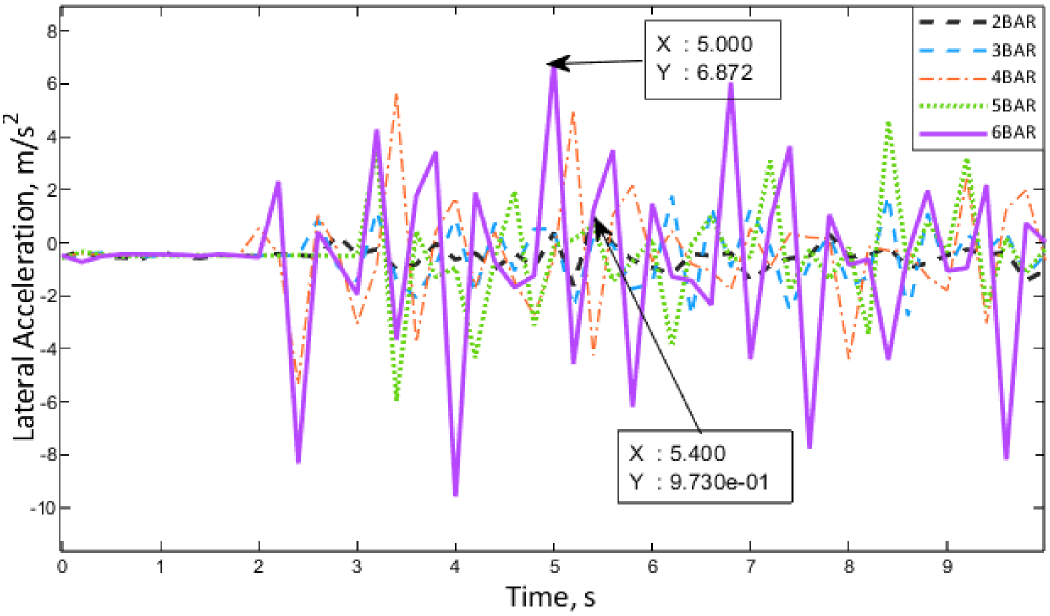


Fig. 9. Time history of body lateral accelerations under different lateral disturbance at C2y=1.8x10^{4}Ns/m

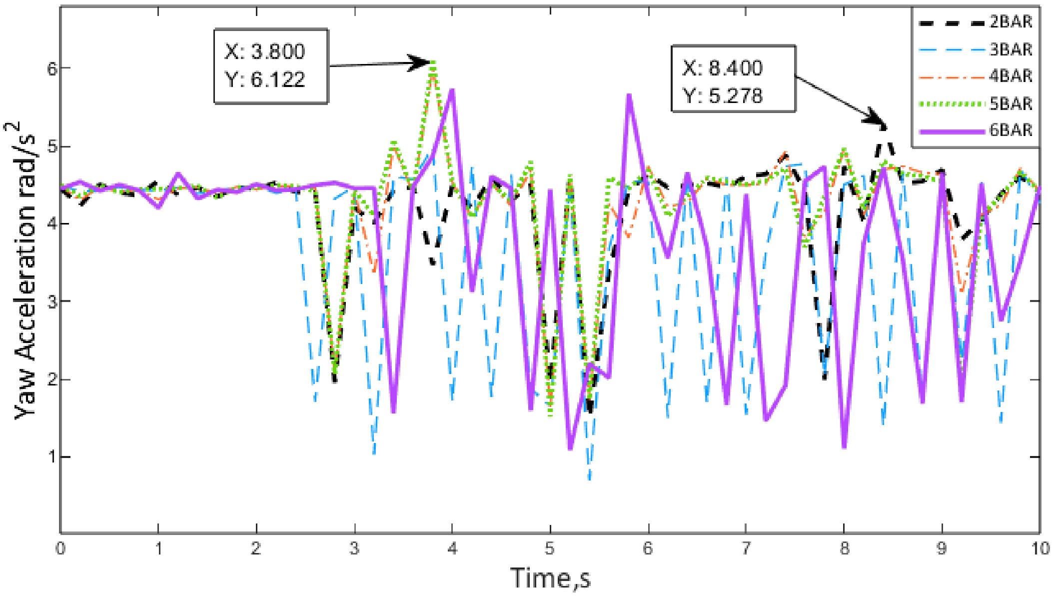


Fig. 10. Time history of body yaw accelerations under different lateral disturbance at C2y=1.8x10^{4}Ns/m

Figures 11 and Figure 12 show the values of maximum bogie lateral acceleration and bogie yaw acceleration motion with various lateral disturbances. The maximum value for bogie lateral acceleration was 7.173 m/s^2 for 6 bars and 1.274 m/s^2 for 2 bars of pressure. Different lateral disturbance conditions provide valuable insights into the dynamics of railway vehicles, particularly at higher pressure. A higher pressure of lateral disturbance with 6 bars will generally result in increased lateral acceleration of the bogie motion. This is because the bogie, which carries the wheels and axles, needs to respond more quickly and exert greater lateral forces to maintain stability. The variation in bogie motion values between high-pressure and low-pressure lateral disturbances underscores the importance of an efficient suspension system. In addition, bogie yaw acceleration also shows a maximum value was 6.215 rad/s^2 at higher lateral pressure and a maximum value of 5.198 rad/s^2 at lower pressure. The yaw motion of the bogie can affect the stability and control of the railway vehicle. It can lead to wheel flange contact with the rail, which may result in increased wear and tear and the potential for derailment. Therefore, advanced suspension systems, such as those with active control, may help mitigate excessive bogie yaw motion by actively adjusting suspension parameters in real-time.

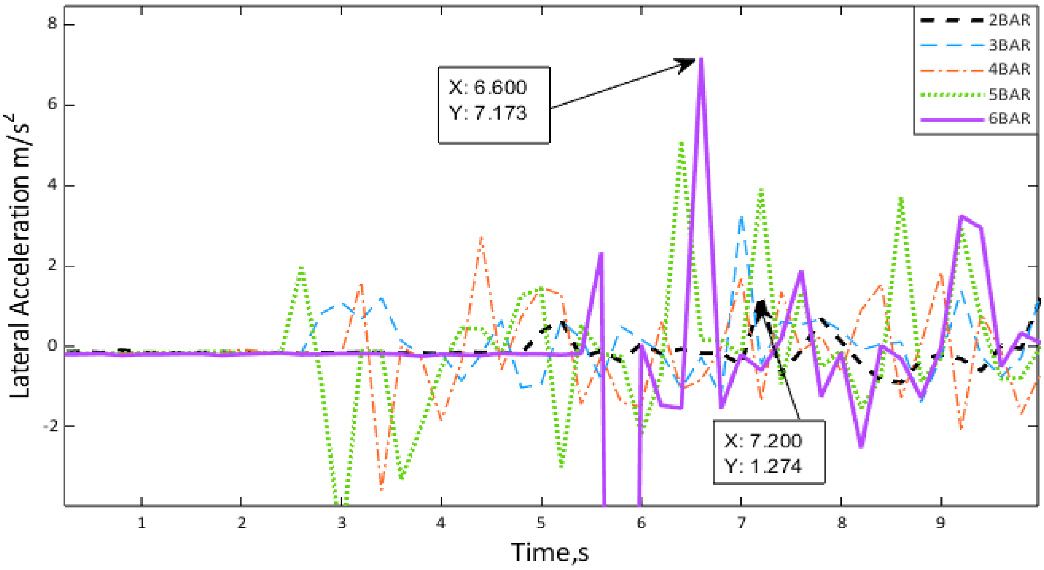


Fig. 11. Time history of bogie lateral accelerations under different lateral disturbance C2y=1.8x10^{4}Ns/m

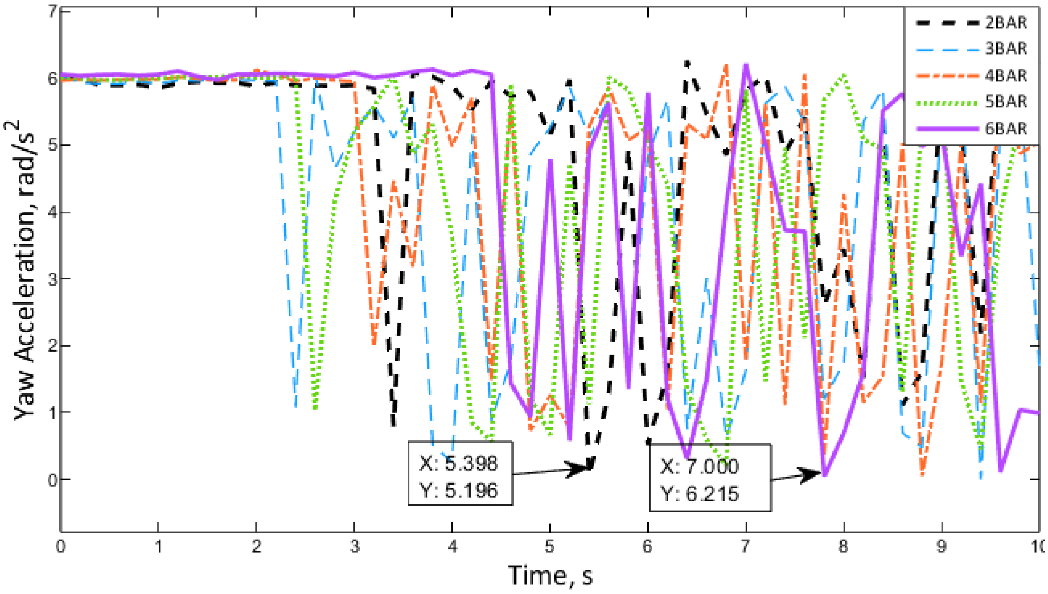


Fig. 12. Time history of bogie yaw accelerations under different lateral disturbance C2y=1.8x10^{4}Ns/m

Higher-speed lateral disturbances, such as strong crosswinds or track irregularities, can lead to an increase in track lateral acceleration. This is primarily due to the lateral forces exerted on the railway vehicle as it encounters these disturbances at higher velocities. Figure 13, shows that the higher pressure gave the higher lateral acceleration with a maximum value 4.235 m/s^2 at 6 bars, and the maximum value for lower pressure at 2 bars was 2.181 m/s^2 while Figure 14 shows the higher lateral pressure on track gave the higher value of 6.224 rad/s^2 in track yawing and low pressure give the value of 6.079 rad/s^2. Excessive yaw motion induced by lateral disturbances can result in increased wear and tear on the track structure. The effects of lateral disturbances on the yaw motion of the track can impact safety and passenger comfort. Table 1 and Figure 15 summarise lateral railway vehicle performance (lateral and yaw acceleration) under different lateral disturbances, showing that the increasing lateral disturbance will contribute to the increasing lateral and yaw acceleration on railway vehicle motion.

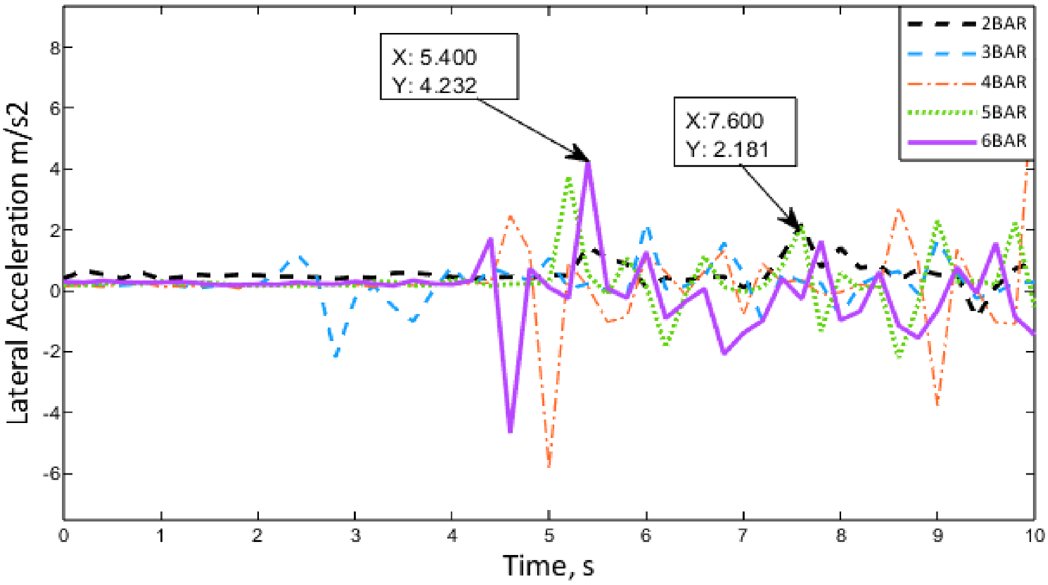


Fig. 13. Time history of track lateral accelerations under different lateral disturbance

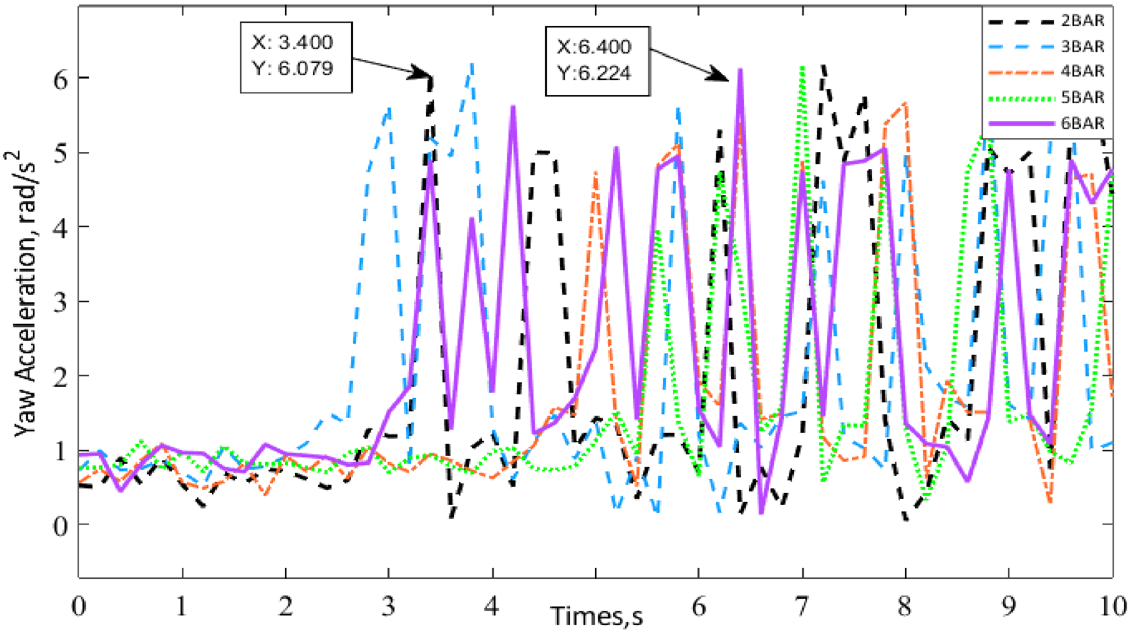


Fig. 14. Time history of track yaw accelerations under different lateral disturbance

Table 1
Lateral railway vehicle performance under different lateral disturbances

Pressure		2BAR	3BAR	4BAR	5BAR	6BAR
Vehicle Motion						
Lateral Acceleration (m/s^2)	Body	0.973	1.795	4.619	5.678	6.872
	Bogie	1.274	1.374	2.725	5.097	7.173
	Track	2.181	2.256	2.754	3.763	4.232
Yaw Acceleration (rad/s^2)	Body	5.278	4.983	5.994	6.122	6.215
	Bogie	5.196	6.124	6.172	6.188	6.215
	Track	6.079	6.195	5.668	6.161	6.224

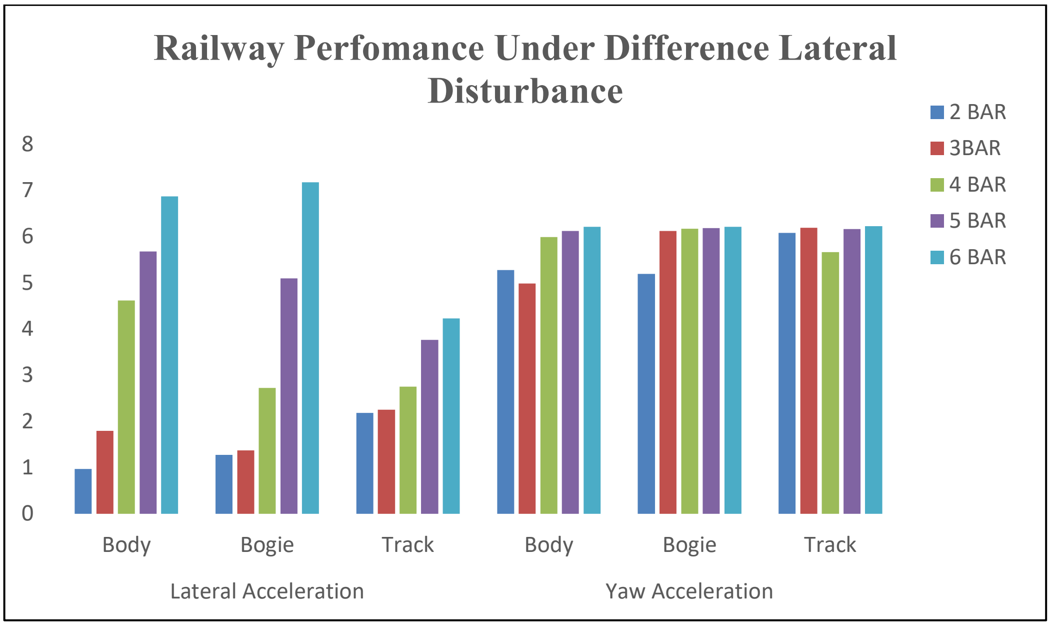


Fig. 15. Graph of railway performance under different lateral disturbance

4. Conclusions

In conclusion, the analysis of the lateral performance of railway vehicles under varying lateral disturbance conditions has provided valuable insights into the dynamic behaviour of these systems. The study revealed that different levels and speeds of lateral disturbances can significantly affect the lateral acceleration, yaw motion, and overall stability of both the railway vehicle and the track. At higher speeds of lateral disturbance will be increased lateral accelerations in the vehicle and greater yaw motion, suggesting a need for enhanced stability control mechanisms. Conversely, at lower speeds, the lateral disturbance had a comparatively minor impact on lateral acceleration with percentage differences of .85.84%, 82.23%, and 48.46% for lateral acceleration on body, bogie, and track while 13.8%,16.4%, and 2.34% for yaw acceleration respectively. Therefore, it highlights the need for advanced control systems and design modifications that can effectively mitigate the effects of lateral disturbances and enhance the overall performance of railway systems.

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