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INVESTIGATING EFFECTIVE FACTORS IN STABILITY AND LATERAL FORCE BETWEEN ROLLER WHEELS IN BALLASTED AND BALLASTLESS TRACKS

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***Abstract*— The cases examined in this article are divided into three main parts. First, various parameters related to locomotives and wagons, such as the suspension system, traction force, braking power, weight, and other factors, will be investigated, and their effects on the forces between the wheel and the rail will be demonstrated. In the second part, the impact of line parameters, generally related to the specifications of the rail, jamb connections, bindings, ballast, or the infrastructure of the line, has been studied. Finally, the article addresses the effect of train performance on stability. The forces between the wheel and the rail are applied in three directions: longitudinal, vertical, and lateral. It should be noted that the focus of this article is on lateral forces, which are divided into two parts: dynamic forces and pseudo forces. These lateral forces are further categorized as static or permanent, and the influence of different parameters on these two types of forces has been investigated. The article explores various factors, such as the distance between the axles of the bogie, friction coefficient, tensile state or braking, profile, etc., to understand their impact on stability.**

***Keywords*— Locomotive, stability, lateral force, dynamic force, adhesion, compliant bogie**

I. INTRODUCTION

The increase in axle load in locomotives and wagons creates numerous associated problems, which can be addressed through careful investigation. To achieve this, precise measurements were conducted using advanced computer systems. Subsequently, the information for each wheel was gathered through corresponding sensors [1], [2]. The curves depicting quasi-static forces and dynamic forces are detailed in the text. It is crucial to note that quasi-static or permanent forces refer to those applied consistently over a period, while dynamic forces denote those applied in an oscillating manner [3]–[5].

II. PROPOSED ALGORITHM

A. The effect of the number of bogie axles on the lateral force between the wheels

As shown in Figure (1), increasing the number of bogie axles and augmenting the curvature of the arch result in an increase in its static side forces. When considering the same conditions in the design of all three bogies and taking into account the degree of curvature of the arch as 1, it can be observed that the alterations in the forces between the wheels are attributed to the size of the wheelbase (the distance between the first and last axles of the bogie) and the number of axles [6], [7].

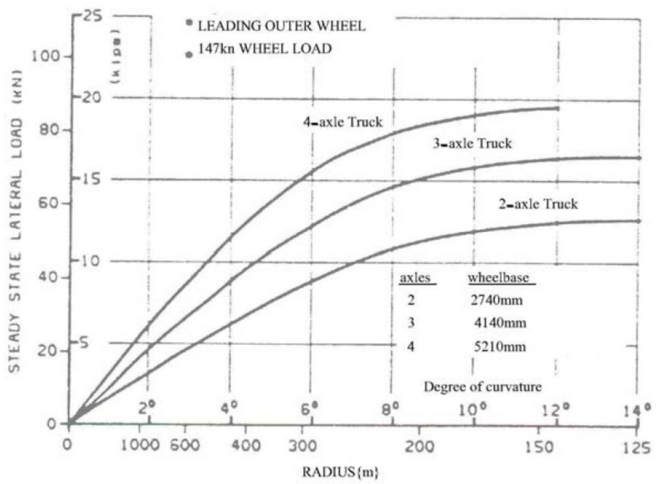

Fig. 1. Relationship between arc radius and lateral force in different bogies

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As the test results have shown, lateral quasi-static forces in four-axle bogies are 30% higher than those in three-axle bogies. Additionally, these forces in 2-axle bogies are 30% less than those in three-axle bogies [8], [9]. It is also observed that increasing the number of bogie axles leads to an increase in the forces between the wheel and rail, and this phenomenon intensifies in steeper arcs [10], [11].

B. **Effect of laxity between bogie parts and tools on side forces between wheel and rail**

Figure 2 illustrates the effect of free play between the wheel (line width) in two states: 9.5mm and 22.2mm. Increasing the clearance (line width) between the wheel and the guide axle enhances the axle's alignment with the curved curvature, consequently reducing the force applied to the wheel. One method to decrease lateral force is to maintain proper alignment. A radial (steerable) bogie achieves this by ensuring that the longitudinal axis of the bogie aligns with the rail [12]–[14].

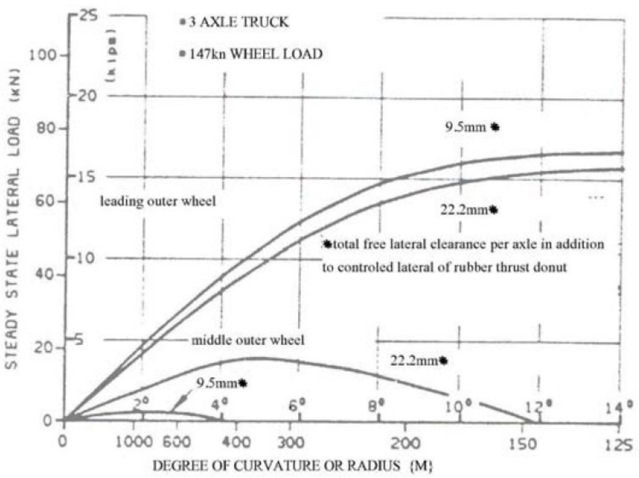

Fig. 2. Relationship between lateral force and free deflection (line width) in different arches

In a theoretical scenario, in an ideal steerable vehicle, all quasi-static lateral forces between the wheel and the rail disappear. However, in reality, for enhanced stability in the system (against the repeated rotation of the bogie in the yaw direction), the wheel and the axle must possess the required rigidity to some extent. This is why the radial direction of the axle and the radius of the arc may not align. For instance, during the braking or acceleration of a locomotive, the created braking or traction force attempts to overcome the control forces of the bogie, hindering effective control when passing through the arch. Consequently, optimal bogie control does not occur. This complexity is why the design of compliant bogies encounters more challenges. Figure 3 compares two types of bogies: normal and radial [15], [16].

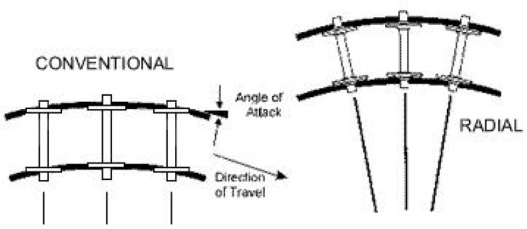

Fig. 3. Radial bogie (steerable) and normal when passing through the arch

C. **The effect of line on lateral forces**

When the curvature of the arc increases, the wheel's creep on the rail also increases, leading to a rise in the rate of creep (as depicted in the diagram in Figure 2). Establishing a line width is essential in arcs, contributing to increased friction between the wheel and the rail, resulting in heightened lateral forces between them. Many bogies experience an increase in lateral forces when navigating curves. In contemporary bogie design, there are sufficient measures in place to address these challenges, particularly in the primary suspension system. However, widening the line width, except in the arc, is not highly effective. Excessive widening of the track can cause the bogie to rotate more in the yaw direction between the two rails. Consequently, lateral creeps increase, leading to a final escalation in lateral forces [17]–[19]. For instance, a mere increase of 10 mm in track width can cause quasi-static lateral forces to increase by more than 10%.

D. **The effect of the amount of creep on the quasi-static side forces**

According to the results of the experiments conducted on locomotives, using sand on the dry rail increases the quasi-static lateral forces between the wheel and the rail by 40%.

E. **The effect of blasstless tracks**

Ballasted and ballast less tracks represent two distinct approaches to railway track structures, each with its own merits and drawbacks. The traditional ballasted tracks rely on a layer of crushed stones to provide support and stability, effectively distributing the load from passing trains [20], [21]. Despite their widespread use, these tracks require regular maintenance to address issues like ballast degradation and track settlement [22]. Conversely, ballast less tracks forego traditional ballast and employ a rigid structure, typically a concrete slab, to support the rail tracks. Kamyab Moghaddam explores advancements in ballastless tracks, aiming to improve the reliability of railway foundations by replacing traditional ballast with materials like concrete and asphalt. He reviewed the application of asphalt and Embedded Rail Systems for urban settings, which has been followed in this research. His conclusion emphasizes the higher construction costs of ballastless tracks [23]. Zhu et al. and Liu et al. have explored tracks that provide advantages such as reduced

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maintenance needs, enhanced stability, and improved control over track geometry, rendering them suitable for high-speed rail and challenging environments. However, the higher initial construction costs and limitations in adapting to ground settlement pose considerations when choosing between the two track systems. Factors like train speed, track alignment, and long-term maintenance play pivotal roles in the decision-making process [24]–[26].

F. **Effect of braking and traction on quasi-static lateral forces**

If we consider a locomotive that is pulling or braking, in this case, there is a significant amount of movement in the direction of the wheel and rail. When passing through the arch, this movement is caused by the creep occurring between the wheel and the rail. Since the maximum friction coefficient between the wheel and rail is limited, the total creep resulting from these movements is also constrained by the friction force between the wheel and the rail [27], [28]. This phenomenon leads to a reduction in the amount of adhesion between the wheel and the rail when passing through the arch, due to the increased lateral creep and the limitation in the total creep. Consequently, the coefficient of adhesion during the locomotive's passage through the arch is less than that on a straight line. Therefore, in mild curves, the effect of braking and acceleration is minimal due to the low amount of creep.

G. **The effect of slack in quasi-static lateral forces**

Figure (4) illustrates the tendency of the wagons to tilt and shear under pressure between them. The lateral clearances between the body and the rail significantly influence the increase in lateral force in the bogie bowl. Besides elevating the starting point, the increase in buff pressure force results in a steeper slope angle. Therefore, to minimize the force on the bogie bowl, it is essential to reduce side slip as much as possible.

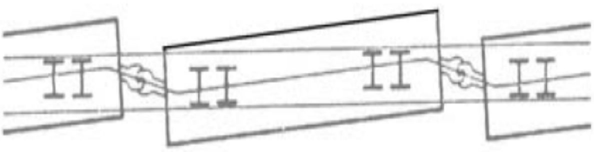

Fig. 4. Tendency to shearing in middle wagons due to Buff compressive force

On the other hand, there is lateral play in the primary suspension system to enhance the transition from the arc, along with play in the secondary suspension system to ensure a comfortable journey. Therefore, it is crucial to find a middle ground that satisfies both requirements. Let's consider a compromise [29], [30].

H. **Effect of shape and dimensions on quasi-static lateral forces**

Figure (4) illustrates the longitudinal dimensions of three points on the wagon that play a role in shearing. The lateral force decreases as the distance between the bogie center (cradle distance) increases. Similarly, the lateral force decreases as the distance between the bogie center and the coupler joint (overhang) decreases. Additionally, the lateral force decreases with an increase in the length of the coupler. One crucial indicator in wagons for generating quasi-static lateral force is the distance from the center of the cradle to the coupler joint, presented as the A/B ratio in Figure (5). The relationship between this ratio and the lateral force applied to the bogie bowl is depicted [31], [32]. A decrease in the A/B ratio is associated with an increase in lateral force. For example, if the A/B ratio is kept constant, the variation in the distance (d) from the cradle has minimal effect on the force applied to the bogie bowl.

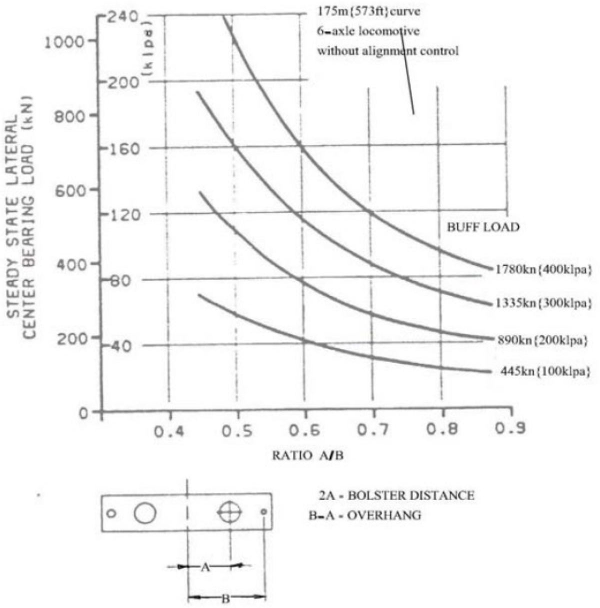

Fig. 5. Relationship between overhang cradles and lateral force

I. **The effect of empty wagons on stability and ratio**

The ratio of lateral force to vertical force is crucial for the stability of the system. The compressive force between the two couplers (Buff force) is transmitted to the wheel through the bogie cup and, from there, to the side rails. This force (L/V) tends to push the wagon wheel off the track. The appropriate and safe ratio lies between 0.5 and 0.6. This value can be slightly exceeded under good track and rail conditions.

All the information was obtained in an experiment where an SD40-2 locomotive (similar to GT26 locomotives) was coupled to a wagon with a swivel-jointed coupler and a long distance between the center of the bogie and the coupler joint (overhang). When dealing with empty wagons and a long

distance between the center of the bogie and the coupler joint, for a ratio of L/V=0.5, only a Buff force equal to 200KN can be applied to prevent derailment [33], [34].
The likelihood of derailment in wagons depends on factors such as the length of the overhang, the length of the wagons, whether the wagons are empty or full, and the distance between the wagon and the locomotive. Typically, railways move heavy loads with several locomotives coupled together, equipped with dynamic brakes. Dynamic braking is a necessary tool for safe driving and movement. If each electric and motor has a dynamic braking ability of 44.5KN, a maximum of 20 axles or a total dynamic braking force of 890KN can be applied. Exceeding this limit would cause the Buff compressive force to exceed its allowed value, resulting in an increased L/V ratio and reduced safety. Therefore, it is not recommended to couple more than three locomotives.

J. **Lateral dynamic forces between wheel and rail**

In Figure (6), the results of an experiment are presented. The experimental conditions include a 6-axle locomotive, a line arc of 610 m, a line circumference of 89 mm, and a weight force of 147KN for each wheel. The set of quasi-static forces is obtained at a speed of 30 mph, equivalent to 31KN. Assuming that the set of quasi-static forces is equal to 40KN at a speed of 57 mph, Figure (6) illustrates that the total side forces amount to 133KN, with the dynamic side force approximately at 93KN.Therefore, based on the information in Figure (6), it can be concluded that about 1/3 of the lateral forces are related to quasi-static forces, while the remaining 2/3 are dynamic forces. For instance, in an experiment where lateral dynamic forces were applied to two sides of the line at a speed of 161 km/h, the maximum dynamic force caused by hunting was 89 KN, with a vibration frequency of 3.7 cycles per second [35].

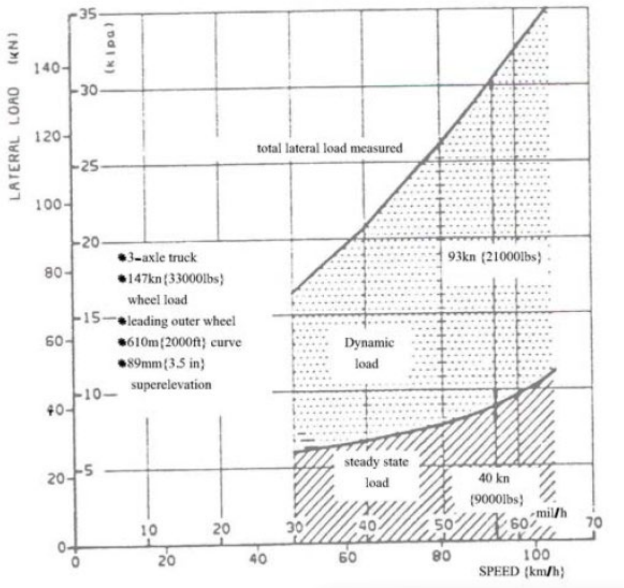

Fig. 6. The relationship between speed and lateral forces (static and dynamic) in the locomotive

Another condition is the testing of the wheel wear profile, which has covered approximately 17,700 km under service conditions and then underwent testing. The reason for this is that, within the initial 56,000 km, the wear is on average 12%, and by 177,000 km, it reaches 17%. This indicates that the wear speed of the profile is higher in the first 56,000 kilometers, but afterward, it decreases. This can be a valuable criterion for the presence of creep and, consequently, lateral forces between the wheel and rail. Therefore, it is recommended that the wheel profile, especially at speeds higher than 113 km/h, should have a cone angle of 1/40 instead of the current 1/20 cone angle (abrasion profile) [36], [37].
The information obtained in the mentioned experiment considers a clearance of 9.5 with regard to the space between the axle head and the bogie frame. It should be noted that clearance is a critical parameter in creating the hunting phenomenon, and at speeds higher than 113 km/h, it is approximately 6.4 mm. For speeds less than 113 km/h, a clearance of about 9.5 mm is recommended.

III. CONCLUSION

The lateral forces applied between the wheel and the rail are divided into two: quasi-static forces and dynamic forces. These forces vary based on the structure of the wagon and the characteristics of the track. Quasi-static forces can be calculated using locomotive design parameters, bogie type, axial load, and arc radius. The act of braking or accelerating the train is a significant factor in creating lateral forces. Friction between the wheel, the presence of contaminated materials, and grease on the surface of the rail, or the use of sand play crucial roles in determining the amount of side forces between the wheel and the rail. Repair and maintenance of the track, as well as the width of the track, have a considerable impact on the lateral forces on the line. The traction force and adhesion coefficient of locomotives decrease when passing through the curve. Improper use of the dynamic brake can cause an increase in side forces.

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