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Article

Evaluating the impact of tire stiffness on dynamic load in three-wheel trucks

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Abstract: The dynamic loads that are produced by the various modes of transportation while they are in motion have a significant impact on the dynamic safety of the bridge or road, as well as the vehicle. Load impacts, which also cause structural damage to transportation infrastructure, are responsible for the catastrophic deterioration of the road and bridge system. In addition to this, it has an effect on the safety of drivers as well as the durability of the components of the vehicle. One of the characteristics that is connected to load is the stiffness of the tire. In this article, the structure of the multi-body system is separated, and the Newton-Euler equation is applied in order to develop the oscillation equation system for the vehicle. The ISO 8608:2016 standard is utilized in order to investigate the impact that varying levels of tire stiffness have on the dynamic load of three-axle vehicles that are driven on class B roads. The findings of the study indicate that the dynamic load on the tire increases in a manner that is proportional to the tire's stiffness at travel speeds. At 90 km/h on a class B road, increasing tire stiffness by 1.5 times raises dynamic load at the front axle from 50,389 N to 50,758 N (1.92%), while reducing stiffness by 0.5 times decreases load to 50,045 N (0.69%). Similarly, rear axle load rises from 46,874 N to 47,626 N (1.64%), indicating tire stiffness's quantitative impact on dynamic load.

Keywords: velocity; dynamic model; 3 axles truck; ISO 8608:2016

1. Introduction

In Vietnam, as well as across the world, three-axle trucks are a common and efficient mode of transportation. The dynamic safety features of the vehicle influence the dynamic loads produced by moving vehicles. Dynamic load is a variable that influences the vehicle's dynamic safety in one direction and road pressure in another, with the former inflicting damage and compromising the durability of vehicle components [1].

The agitation of the road surface is random and cyclical, leading to dynamic loads that are also random and cyclical. The interaction mechanism between the tire and the road surface, which governs the generation and transmission of dynamic loads, is illustrated in **Figure 1**. These loads react by causing the bridge/road surface to oscillate, which in turn causes micro-cracking of the structure. Additionally, dynamic loads have the potential to alter the longitudinal and lateral forces exerted by the wheels, which can impact the dynamic safety of the vehicle and cause wear on the tires and the road. Wheel separation and a loss of power transmission may result from dynamic loads on the return stroke [2].

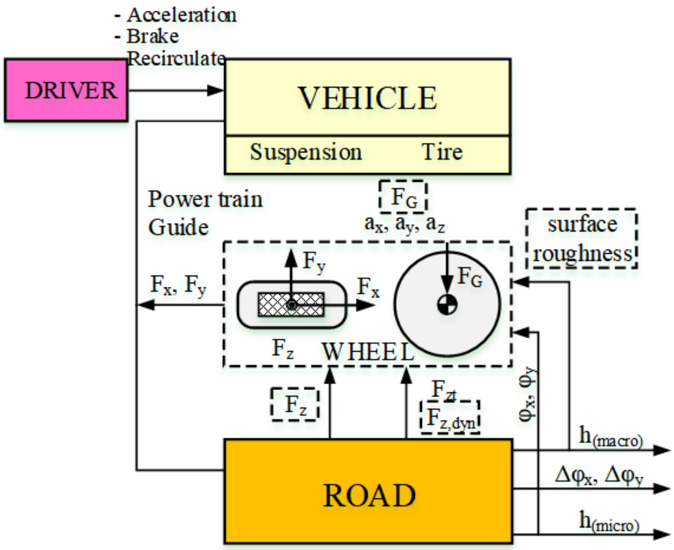

Figure 1. Relationship between tires and roads [2].

Static and dynamic loads on 3-axle trucks are recognized as factors that contribute to road rutting [3]. Static and dynamic loads from 3-axle trucks contribute to road rutting. The magnitude of the dynamic load transmitted to the road relates to vehicle vibrations, which are influenced by vehicle design and operational factors. Design factors include total vehicle mass, axle load distribution, vehicle geometry, suspension characteristics, and tire characteristics. Operating factors include vehicle speed, load level, tire pressure, etc. [4]. Dynamic load is a factor that influences two aspects: it increases road pressure, which can cause damage and reduce the durability of vehicle parts; conversely, it decreases the vehicle's dynamic safety. Dynamic load depends on four factors: speed, road surface, load (weight of cargo carried), and tire stiffness [5]. Dynamic load ($F_{z,dyn}$) is generated by the oscillation of mass components under the agitation of the road surface. Road surface irregularities impact dynamic loads, impacting both the road and vehicles, as illustrated in **Figure 2** [6,7].

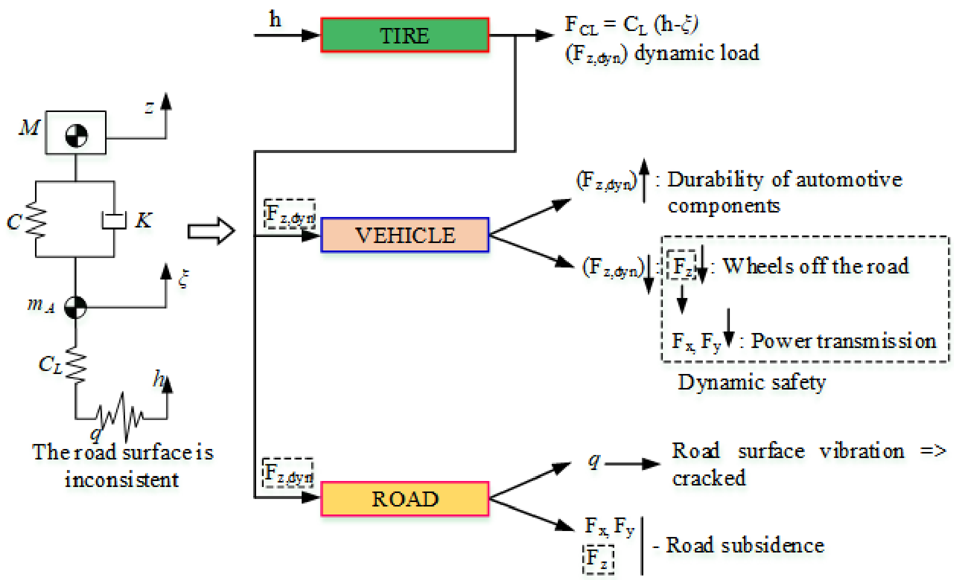

Figure 2. The diagram shows dynamic load effects.

A parameter that is frequently used to characterize the magnitude of dynamic loads is known as the dynamic load coefficient (DLC); this ratio is defined as the average radial elastic force of the tire divided by the static load on the tire. Several studies have shown that DLC increases with increasing road roughness, vehicle speed, tire pressure, and suspension stiffness [8].

Dynamic loads are influenced by factors such as speed, road type, and load level. Therefore, the assessment criteria related to both the vehicle and the road are as follows: Dynamic load coefficient (DLC), Dynamic Load Stress Factor (DLSF), load factor (k_d), max wheel reaction ($F_{z,max}$). These evaluation criteria are mentioned by many researchers [1,9–12].

1.1. Dynamic load coefficient

The dynamic load coefficient is frequently utilized in the assessment of dynamic loads. As discussed in the previous section, it is crucial to consider both the static load component and the dynamic load when evaluating the impact of a vehicle's load on the road. The dynamic load can reach a maximum of 20% to 30% of the static load [8]. The dynamic load factor is determined using the following mathematical [9,13]:

$$\mathrm{DLC} = \frac{\sigma}{F_{mean}}. \tag{1}$$

In there:

σ: Standard deviation of the force applied to the wheel axle, $\sigma = \mathrm{RMS}\,(F_{z,dyn})$.

F_{mean}: Static force on the wheel axle, $F_{mean} = F_{zt}$.

DLC is frequently utilized to assess dynamic loads using a random excitation function. Under normal operating conditions, DLC values typically range from 0.05 to 0.3 [6].

1.2. Dynamic load stress factor (DLSF)

DLSF is applied when assessing the impact of dynamic loads on roads, calculated using the following mathematical [11]:

$$\mathrm{DLSF} = 1 + 6\mathrm{DLC}^2 + 3\mathrm{DLC}^4. \tag{2}$$

DLSF assesses road damage using a fourth-order ratio linked to the dynamic load factor. Research indicates that a DLSF value of 1.56 or lower is deemed a road-friendly threshold for determining vehicle dynamic parameters [12].

1.3. Load factor (k_d)

Load factor (k_d) is utilized to assess how the road affects the wheel reaction force F_z, which is defined as follows [1]:

$$k_d = \frac{F_z}{F_{zt}}; F_z = F_{zt} + F_{z,dyn}. \tag{3}$$

In there:

F_z: Vertical reaction force of the wheel, (N);

F_{zt}: Vertical reaction force of the wheel, static load, (N);

$F_{z,dyn}$: Vertical dynamic load, (N).

For a specific load level, F_{zt} remains constant. The variation in F_z is influenced by the coefficient k_d, which typically hovers around the value of 1. The coefficient k_d is utilized to assess the degree of change in F_z during both the compression and return strokes of the suspension system. A value of k_d greater than 1 indicates the impact of load on the road and the durability of vehicle components; $k_d \leq 1$ is used to evaluate the dynamic safety of the vehicle. When F_z increases, it impacts the alignment and durability of the part. Conversely, when F_z decreases, it results in a reduction of the vertical and horizontal force components, which affects the ability to transmit force and provide guidance. When $F_z = 0$ is reduced, the wheel will separate from the road surface. When it is necessary to evaluate the dynamic load interaction between the vehicle and the road, k_{dmin} and k_{dmax} can be used, defined as follows [12]:

$$k_{d\,min} = 1 + \frac{\min\left(F_{z,dyn}\right)}{F_z}; 0 \leq k_{d\,min} \leq 1. \tag{4}$$

Some limitations of kdmin include the following:

$k_{dmin} = 0.5$: warning limit;

$k_{dmin} = 0$: limited intervention, wheel separation from the road surface ($F_z = 0$).

$$k_{d\,max} = 1 + \frac{\max\left(F_{z,dyn}\right)}{F_{zt}}. \tag{5}$$

Road surface roughness is random:

$$k_{d\,max} = 1 + \frac{1.64 \times \mathrm{RMS}\left(F_{z,dyn}\right)}{F_{zt}}, \tag{6}$$

$k_{dmax} \leq 1.5$, this is the limit set to ensure the durability of vehicle details [12].

1.4. Max wheel reaction ($F_{z,max}$)

The maximum force value is transmitted to the road surface during the vehicle's travel for a certain period of time and is determined as follows [8]:

$$F_{zij,max} = \max\left(F_{z(ij)}\right); (i = 1:1:6, j = 1,2), \tag{7}$$

$F_{z(ij)}$ represents the wheel reaction force at wheel ij, which is used to evaluate the maximum wheel load when the load level changes.

When it comes to the research of automobile dynamics, particularly for multi-axle vehicles, it is essential to investigate the dynamic loads that are operating on the wheels and vehicle chassis structure. Recent studies have concentrated on a variety of elements, including the influence of the road surface, the properties of the tires, the suspension systems, and the modeling of the overall dynamics of the vehicle. Nevertheless, these studies still have a number of limitations, which create gaps that require further attention and investigation.

When it comes to dynamic load, the pavement profile is one of the most significant aspects to consider. The study conducted by Mieteń and colleagues [9] aimed to examine the influence of various types of pavement on the dynamic load that was delivered to the wheels. As the pavement roughness increased, the results demonstrated that the amplitude of wheel load oscillation also rose dramatically, which resulted in an increase in the amount of stress that was applied to the chassis and suspension. The phenomenon of resonance is more noticeable while the vehicle is going at high speeds, which is when it is most likely to occur. In a similar manner, Misaghi and colleagues [14] investigated the impact that the combination of pavement roughness and suspension characteristics had on dynamic load. The results of this investigation demonstrated that the arrangement of the suspension systems, in addition to the pavement profile, plays a significant role in either amplifying or decreasing the dynamic load. In situations where the suspension does not have enough damping qualities, the dynamic load that is transmitted to the pavement will be increased, which will have a severe impact not only on the vehicle but also on the infrastructure. In addition, Kang et al. [15] extended the research direction to the field of dynamic load impact on transport infrastructure. The findings demonstrated that dynamic loads not only contribute to the acceleration of the rate at which road surfaces are damaged, but they also play a role in the development of damage such as rutting and cracking of the road surface. When it comes to the design and operation of transport vehicles, this highlights how important it is to control dynamic loads.

Tires are the elements that act as intermediaries in the transmission of force between the vehicle and the road surface. As a result, they play a crucial role in the production of dynamic load. Yoo et al. [16] created a load-dependent tire-road friction model, which made it possible to simulate the dynamic behavior of multi-axle trucks with greater precision. The results of this model demonstrate that the friction coefficient is not constant but rather varies depending on the load and the contact circumstances, which in turn has an effect on the motion stability of the vehicle. While this was going on, Do et al. [17] concentrated on determining the longitudinal stiffness of the tire in real time while taking into account the dynamic properties of the tire. A significant improvement in the accuracy of the dynamic model can be achieved by continuously updating the tire stiffness, as demonstrated by the findings of the research found in Do et al. [17]. Additionally, Qin et al. [18] suggested a method that could estimate the stiffness of tires in real time by integrating the GDM and RLS algorithms. This method would be useful for autonomous vehicle systems. Furthermore, Liu et al. [19] conducted research on the static stiffness characteristics of high-load capacity tires, which included airless tires. According to the findings, the structure of the tread had a substantial impact on the load-carrying ability of the tire as well as the deformation of the tire. Zang et al. [20] conducted more research on run-flat tires using a nonlinear pressure distribution model. This model assisted in providing a more precise description of the behavior of the tire under specific conditions, such as pressure loss.

Recent research has focused on frequency-domain tire modeling and rheological characterization, in addition to the traditional stiffness-based tire models, to improve the representation of dynamic load transmission. For instance, frequency-response-based identification methods were proposed to describe the tire behavior under different excitation frequencies, while viscoelastic models allow a more realistic description of energy dissipation and hysteresis effects in tire-road interaction [21, 22]. These approaches have higher modeling fidelity than simple linear stiffness assumptions. The combination of such methodologies can improve the accuracy of dynamic load prediction significantly and will be considered in future extensions of this work.

There is a significant contribution made by the suspension system to the reduction of vibrations and the regulation of the load that is transmitted from the wheels to the frame of the vehicle. A hydro-pneumatic suspension system was utilized by Long et al. in order to carry out dynamic load simulations of big trucks [23]. This suspension system was able to greatly minimize the amplitude of load vibrations when compared to conventional suspension systems, as demonstrated by the findings of the study. In their study, Qi and colleagues [24] constructed a dynamic model for specialized vehicles that takes into account the impact of both the speed of the vehicle and the characteristics of the road surface. The findings of this study offer a more thorough perspective on the dynamic load variation that occurs under a variety of operating scenarios. On a more advanced level, Dantas et al. investigated the impact that the configuration of the truck had on the strength of the frame [25]. According to the findings, an unequal distribution of dynamic load between axles can result in significant local strains, which in turn reduces the total lifespan of the frame's structural components.

Despite existing studies on vehicle dynamic loads, the quantitative influence of tire stiffness on multi-axle truck dynamic loads under ISO 8608:2016 road conditions remains insufficiently clarified. This study develops a comprehensive multi-body dynamic model based on the Newton–Euler approach for a three-axle truck with dependent and balanced suspension systems. The novelty of this work lies in systematically evaluating the effect of tire stiffness variation (0.5–1.5 times nominal values) on dynamic load indicators, including maximum wheel force and DLC, over a wide speed range (30–90 km/h). The results provide quantified relationships that support optimal tire stiffness selection to improve both vehicle durability and road friendliness.

The rest of the paper is organized as follows. Section 2 introduces the dynamic model development with the Newton–Euler method, Section 3 discusses the simulation results and analyzes the dynamic load properties, and Section 4 concludes the paper with main findings and suggestions.

2. Building a model to assess the effect of tire stiffness on the dynamic load of three-axle trucks

The force acting on a truck when it moves on the road is determined based on its dynamic model, in which the front axle has a dependent suspension system, and the two rear axles have a balanced suspension system. There are various methods to establish a system of equations that describes the dynamics of a car, depending on the specific level and parameters to be calculated. In this study, the author employs the method of decomposing the structure of the multi-body system to construct the dynamic model. The steps are outlined as follows:

- Analyze the chassis structure, suspension type, and tire type and make assumptions;
- Definition of fixed coordinate systems and physical coordinate systems;
- Separating the structure of the multi-body system and analyzing the internal forces within the suspension system, as well as determining the interaction force between the tire and the road;
- Construct the Newton–Euler equations for the objects and establish connections between them based on the modules of the system;
- Solving systems of differential equations by algebraic methods.

After solving the system of differential equations, use the obtained results to conduct a survey and evaluate how tire stiffness influences the dynamic load of three-axle trucks traveling on uneven roads.

2.1. Vehicle structure analysis

Three-axle trucks exhibit a complex structure, with axles positioned far apart and unevenly. The first axle serves as the guiding axle and employs a dependent suspension system. The configuration of the front dependent suspension and rear balanced suspension system is illustrated in **Figure 3**. In contrast, the second and third axles function as active axles, utilizing a balanced suspension system. The axles connect to the chassis through a suspension system with leaf springs. This system, described by internal forces, functions nonlinearly. The tire-road reaction forces represent the vertical deformations experienced by the elastic wheels. Additionally, the interaction between the tire and the road involves longitudinal forces.

Figure 3. The front axle dependent suspension and the rear axle balanced suspension are features of 3-axle trucks.

Such structural analysis reveals that the following masses make up the vehicle:

- The suspended mass is positioned at the center C of the vehicle;
- The unsprung mass of the three axles, located at the center A_i of the axles, is linked to the suspended mass through elastic members and shock absorbers.
- When examining how a vehicle bounces while traveling in a straight line, it can move in three ways (three degrees of freedom): it can move vertically along the Z-axis and can rotate around the Y-axis and X-axis;
- Z_C represents the displacement of the suspended mass along the Z axis;
- Z_{A1}, Z_{A2}, and Z_{A3} represent the displacements of the unsuspended mass at the locations of the first, second, and third axles in the Z direction. We define the

indices as (i = 1:1:3; j = 1, 2).

C_{ij} —The stiffness of the suspension springs on the front, middle, and rear axles is measured for both the right and left sides.

K_{ij}—The damping coefficient of the suspension on the front, middle, and rear axles is measured for both the right and left sides.

CL_{ij} —Tire stiffness at the front, middle, and rear wheels on the right and left.

KL_{ij} —Damping coefficient at the front, middle, and rear wheels on the right and left.

ξ_{ij}, ξ_{Aij}—Displacement occurs at the connection points between the vehicle axle and the suspension system.

l_1, l_2, l_3—Distance from the center of the vehicle to the centers of the front, middle, and rear axles.

w—Distance from the center of the vehicle to a left or right wheel alignment point.

b—Distance from the center of the vehicle to the left or right wheel.

h_{ij}—Force acting from the road surface at the contact points with the wheel.

Ignore the impact of wind on the vehicle's motion;

The vehicle chassis is completely rigid and it exhibits no torsion;

Ignore the relative horizontal displacement between the suspended and unsuspended masses; only consider longitudinal and lateral sway;

Wheel contact point with the road surface;

Road excitation only considers road bumps, ignoring deformation.

The complete spatial dynamic model of the three-axle truck used in this study is illustrated in **Figure 4**.

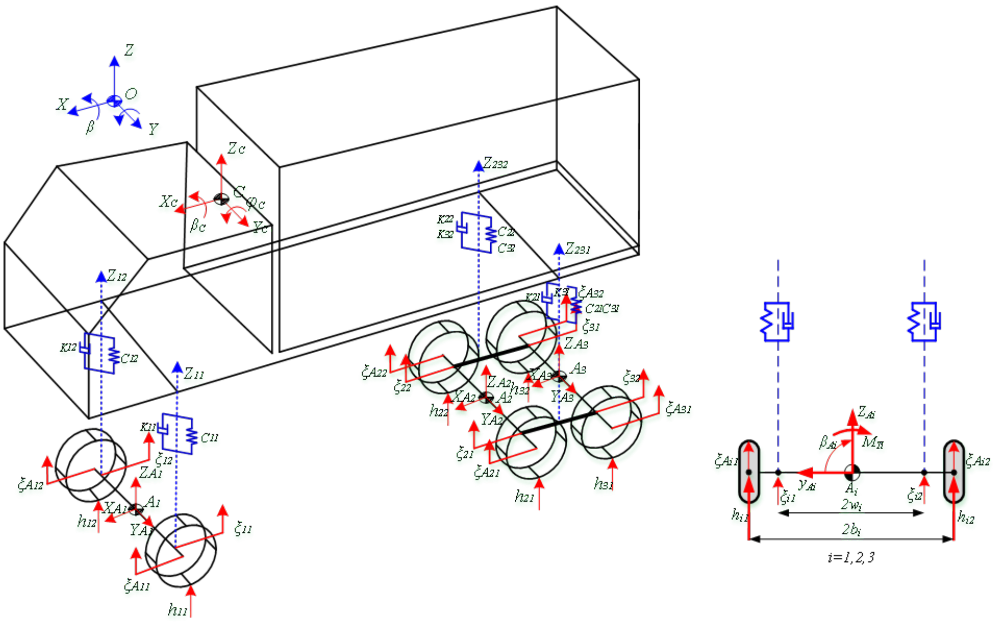

Figure 4. Model of the vibration of a 3-axle truck in space.

2.2. The force that connects the wheel to the road surface

The connection between the wheel and the road is characterized by three forces: the vertical reaction force F_{zij}, the longitudinal force F_{xij}, and the lateral force F_{yij}.

These forces vary continuously over time, influenced by factors such as tire structure, road roughness, and the driver's control actions. Consequently, the precision of the oscillation dynamics model relies on the accurate simulation of the forces F_{xij}, F_{yij}, and F_{zij}. The tire–road interaction forces considered in the model are illustrated in **Figure 5**.

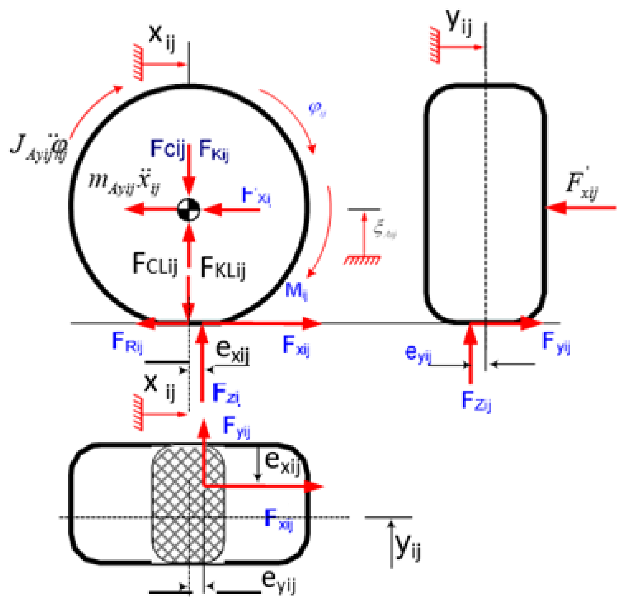

Figure 5. Tire-road bond force diagram.

The mathematical formula determines the tire-road binding forces F_{xij}, F_{yij}, and F_{zij}, which cause the truck to move.

$$\begin{cases} F_{xij} = F_{zij}\varphi_{xij} \\ F_{yij} = F_{zij}\varphi_{yij} \\ F_{zij} = \begin{cases} F_{Cij} + F_{Kij} + F_{Gij} & \text{when } h_{ij} - \left[\xi_{Aij} - f_{ij}^{t}\right] \geq 0 \\ 0 & \text{when } h_{ij} - \left[\xi_{Aij} - f_{ij}^{t}\right] < 0 \end{cases} \end{cases} . \tag{8}$$

The elastic forces of the tire, F_{CLij} are calculated as follows:

$$F_{CLij} = \begin{cases} C_{Lij}\left(h_{ij} - \xi_{Aij}\right) \text{ when } h_{ij} - \left[\xi_{Aij} - f_{ij}^{t}\right] \geq 0 \\ 0 \quad \text{when } h_{ij} - \left[\xi_{Aij} - f_{ij}^{t}\right] < 0 \end{cases} . \tag{9}$$

2.3. Dynamic equation for a three-axle truck

2.3.1. Dynamic equations of sprung mass

The longitudinal coordinate system adopted for deriving the equations of motion is shown in **Figure 6**.

The differential equation that describes the vertical oscillation and swing angle of a sprung mass about the axis Cy is expressed as follows:

Vertical dynamic equation for the sprung mass:

$$\begin{aligned} m_C\left(\ddot{z}_c - \dot{\varphi}_c\dot{x}_c\right) = F_{C11} + F_{K11} + F_{C12} + F_{K12} + F_{C21} + F_{K21} \\ + F_{C22} + F_{K22} + F_{C31} + F_{K31} + F_{C32} + F_{K32}. \end{aligned} \tag{10}$$

The dynamic equation outlines the roll angle of the sprung mass:

$$J_{yc}\ddot{\varphi}_C = -\left(F_{C11} + F_{K11} + F_{C12} + F_{K12}\right) l_1 + \left(F_{C21} + F_{K21} + F_{C22} + F_{K22}\right) l_2 + \left(F_{C31} + F_{K31} + F_{C32} + F_{K32}\right) l_3. \quad (11)$$

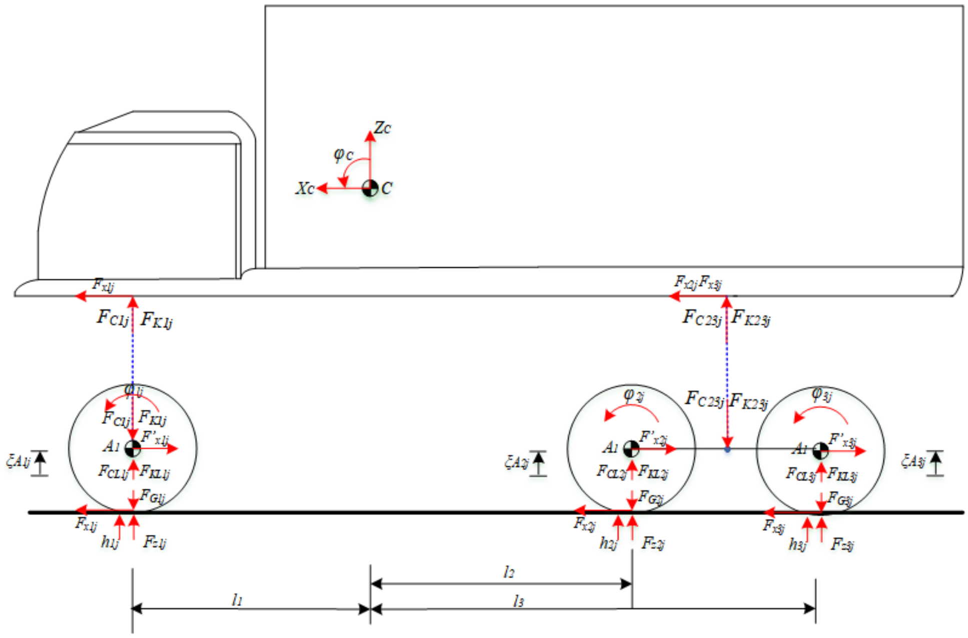

Figure 6. Coordinate system for a three-axle truck in the longitudinal plane (XOZ).

Figure 7 presents the coordinate system used to describe the lateral and roll motions of the vehicle body.

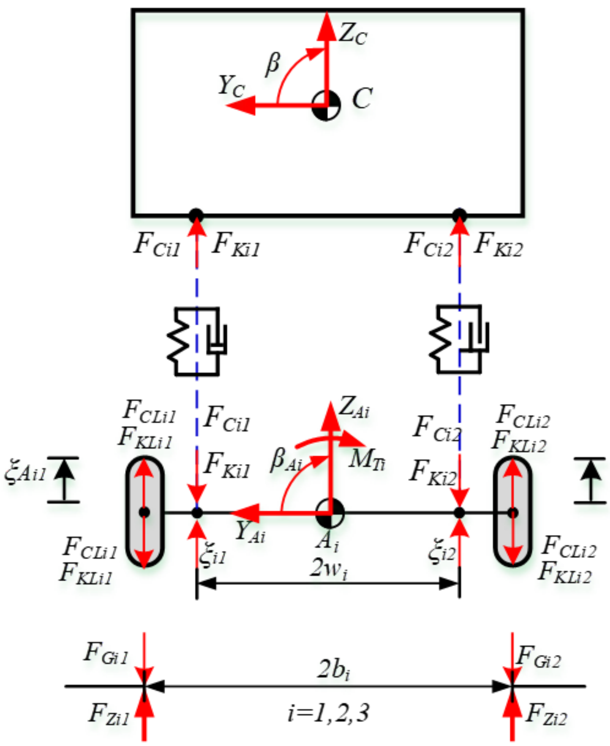

Figure 7. Coordinate system for a three-axle truck in the horizontal plane (YOZ).

The dynamic equation outlines the pitch angle of the sprung mass:

$$\begin{gathered} J_{xC}\ddot{\beta}_C = (F_{C11} + F_{K11} - F_{C12} - F_{K12})\, w_1 \\ + (F_{C21} + F_{K21} - F_{C22} - F_{K22})\, w_2 + (F_{C31} + F_{K31} - F_{C32} - F_{K32})\, w_3. \end{gathered} \tag{12}$$

2.3.2. Dynamic equations of unsprung mass

Three equations describe the vertical motion of the unsprung mass:

$$\begin{gathered} m_{Ai}\ddot{z}_{Ai} = F_{CLi1} + F_{KLi1} + F_{CLi2} + F_{KLi2} - F_{Ci1} - F_{Ki1} - F_{Ci2} - F_{Ki2}, \\ i = (1, 2, 3). \end{gathered} \tag{13}$$

Three equations describe the pitch angle of the unsprung mass:

$$\begin{gathered} J_{Axi}\ddot{\beta}_{Ai} = (F_{Ci1} + F_{Ki1} + F_{Ci2} + F_{Ki2})\, w_i + \\ (-F_{CLi1} - F_{KLi1} - F_{CLi2} - F_{KLi2})\, b_i, i = (1, 2, 3). \end{gathered} \tag{14}$$

3. Survey to evaluate the dynamic loads acting on vehicles

According to the ISO 8608:2016 standard, there are various road quality categories ranging from A to H, as presented in **Figure 8**, with road type A having the highest quality and road type H having the lowest quality [26]. Road surface roughness is categorized into these different road quality types. The author of this survey investigates the movement of vehicles on road type B, which is characterized by poor quality; trucks in Vietnam regularly utilize this type of road since it is available to them. Due to the poor condition of road type B, the survey to determine the dynamic load on the vehicle is conducted at speeds ranging from 30 to 90 km/h, with each speed incrementing by 10 km/h. This is done in order to determine the dynamic load.

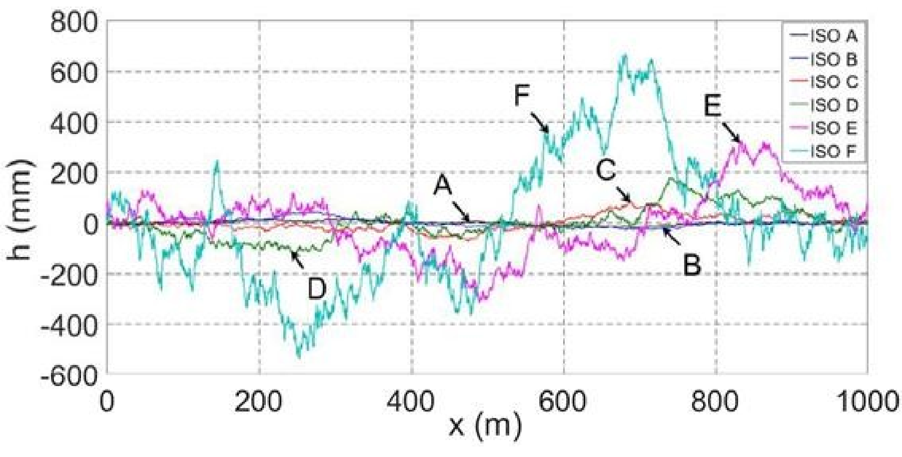

Figure 8. The roughness of road surfaces is defined by the ISO 8608:2016 standard.

Figures 9 and **10** describe the dynamic load of the vehicle at the front and rear wheels, respectively, when moving on a type B road at a speed of 30 km/h for a distance of 250 m. **Figures 11** and **12** describe the dynamic load of the vehicle at the front and rear wheels, respectively, when moving on a type B road at a speed of 90 km/h for a distance of 250 m. **Figures 13** and **14** illustrate the maximum dynamic loads at the front and rear wheels of a vehicle traveling on a type B road as the speed increases from 30 km/h to 90 km/h. At 30 km/h, the maximum load at the front wheel (F_{z1max}) is 49,982 N, while the maximum load at the rear wheel (F_{z3max}) is 45,588 N. When the vehicle accelerates to 90 km/h, F_{z1max} rises to 50,389 N, and F_{z3max} increases to 46,874 N. The numerical values of the maximum wheel loads are summarized in **Table 1**.

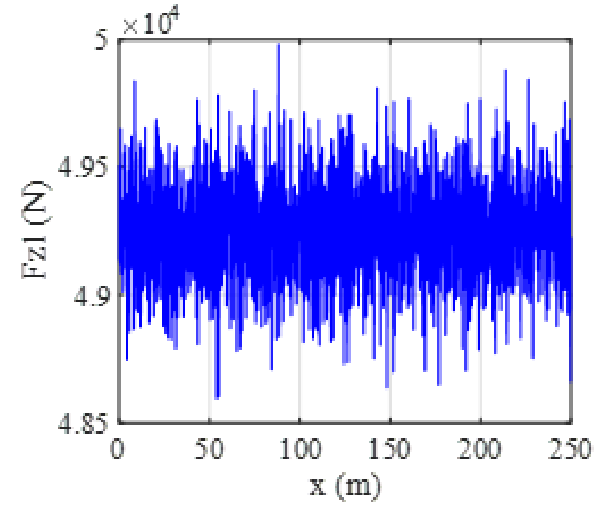

Figure 9. Front wheel dynamic load (F_{z1}) at a speed of 30 km/h on a class B road.

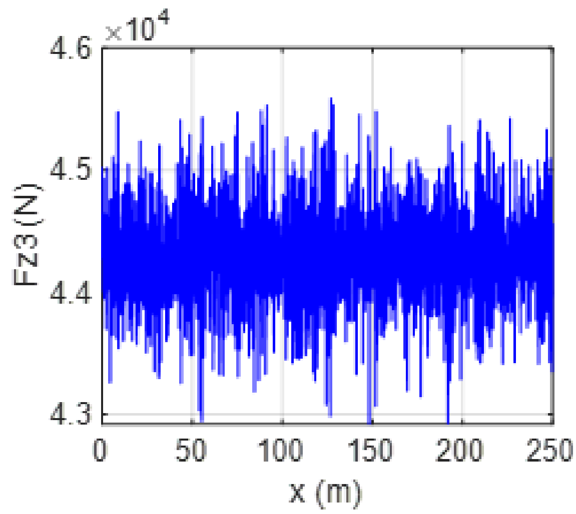

Figure 10. Rear wheel dynamic load (F_{z1}) at a speed of 30 km/h on a class B road.

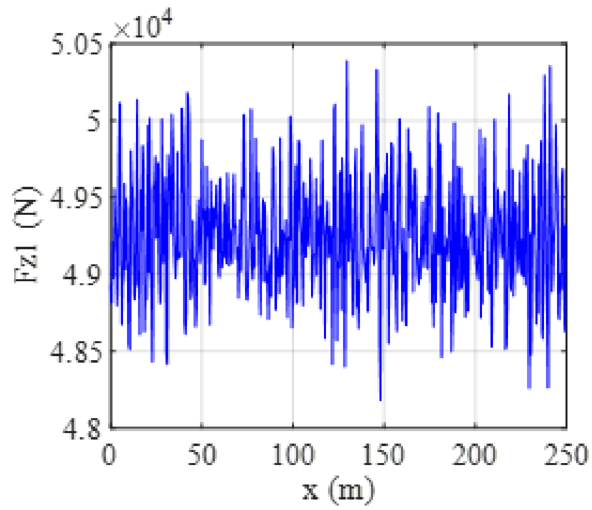

Figure 11. Front wheel dynamic load (F_{z1}) at a speed of 90 km/h on a class B road.

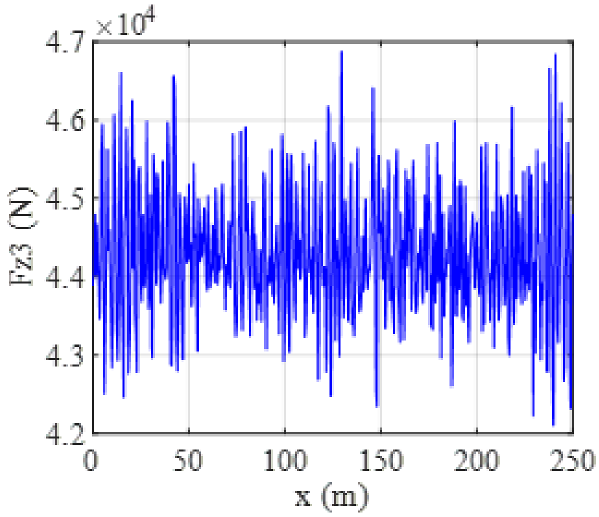

Figure 12. Rear wheel dynamic load (F_{z1}) at a speed of 90 km/h on a class B road.

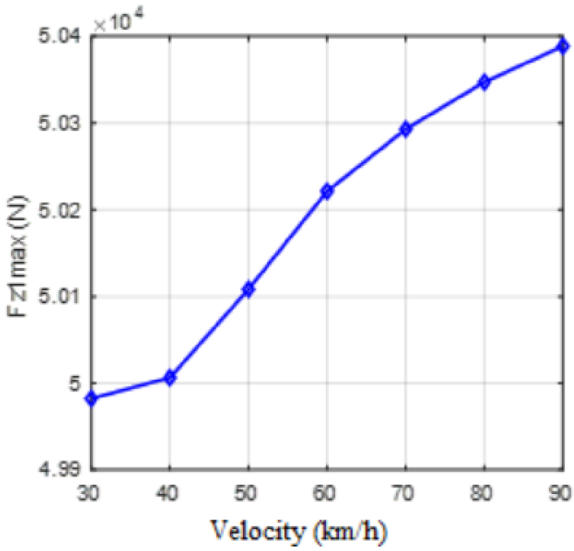

Figure 13. The maximum dynamic load at the front wheel (F_{z1max}) on a class B road occurs at speeds between 30 and 90 km/h.

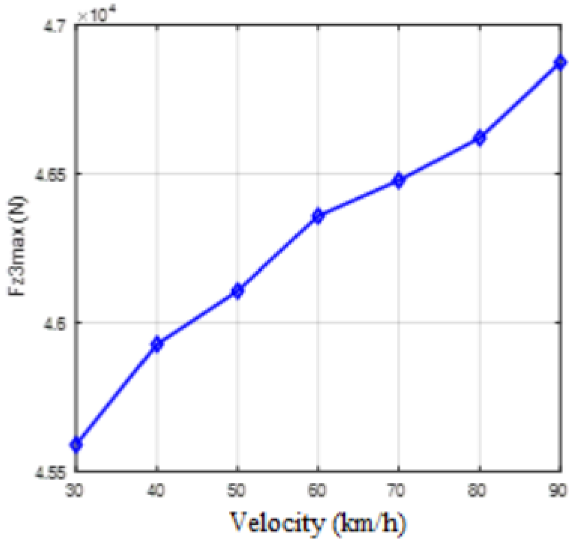

Figure 14. The maximum dynamic load at the rear wheel (F_{z3max}) on a class B road occurs at speeds between 30 and 90 km/h.

Table 1. Maximum dynamic loads at the front and rear wheels on class B roads.

Velocity (km/h)	30	40	50	60	70	80	90
F_{z1max} (N)	49,982	50,006	50,108	50,221	50,293	50,347	50,389
F_{z3max} (N)	45,588	45,927	46,106	46,358	46,477	46,621	46,874

The author assesses the dynamic load coefficient at different moving speeds and analyzes the vehicle's dynamic load using the initial mathematical model. The calculated DLC values corresponding to different vehicle speeds are listed in **Table 2**.

Table 2. Dynamic load coefficient values for the front and rear wheels on a class B road at various speeds.

Velocity (km/h)	30	40	50	60	70	80	90
DLC (F_{z1})	0.021	0.025	0.028	0.032	0.038	0.044	0.051
DLC (F_{z3})	0.027	0.033	0.040	0.044	0.051	0.059	0.068

The relationship between DLC and vehicle speed is illustrated in **Figure 15**. According to Buhari et al. [6], the surveyed DLC values at the front and rear axles on a type B road, with speeds ranging from 20 to 90 km/h, indicate that the car meets the dynamic load conditions specified by the DLC criteria.

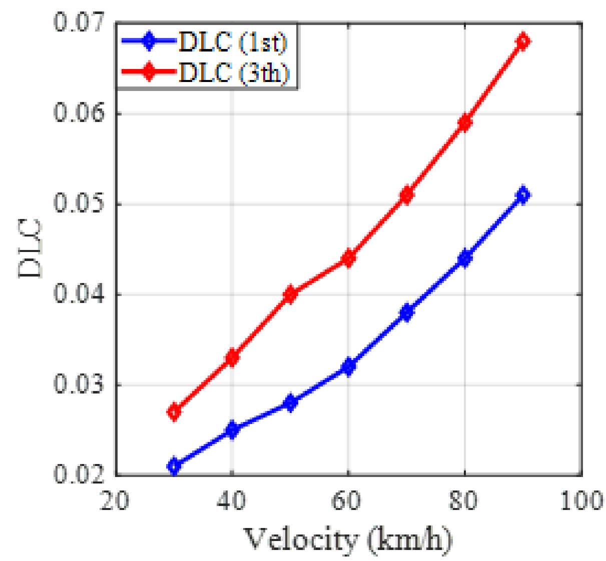

Figure 15. DLC on a class B road, speed range 30–90 km/h.

The author assesses the dynamic load coefficient value to evaluate dynamic loads at various moving speeds and also compares the maximum dynamic load coefficient (K_{dmax}). **Table 3** summarizes the maximum dynamic load factor values obtained at different vehicle speeds.

Table 3. On type B roads with varying moving speeds, the maximum dynamic load factor values are found at the front and rear wheels.

Velocity (km/h)	30	40	50	60	70	80	90
K_{d1max}	1.08	1.11	1.14	1.15	1.17	1.20	1.21
K_{d3max}	1.09	1.13	1.15	1.17	1.20	1.22	1.24

The influence of vehicle speed on the maximum dynamic load factor is presented in **Figure 16**. On a type B road, the results of the analysis shown above indicate that the maximum K_{dmax} value at the front axle is 1.21 when the vehicle is moving at a speed of 90 km/h, and the largest K_{dmax} value at the rear axle is 1.24 when the vehicle is moving at the same speed. It is stated in Li et al. [12] that the vehicle guarantees the longevity of the components that make up the vehicle.

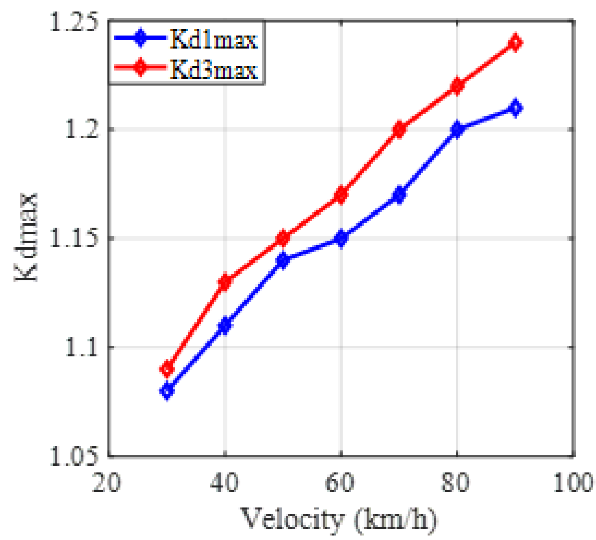

Figure 16. K_{dmax} on a class B road, speed range 30–90 km/h.

The stiffness of the tires on the front axle is defined as C_{L1} = 690,000 N, while the stiffness of the tires on the rear axle is defined as C_{L2} = C_{L3} = 1380,000 N. Adjusting the tire stiffness by a factor of x, which can vary from 0.5 to 1.5 in increments of 0.1, is what the author does in order to make the tire more or less rigid. By making this modification, it is possible to achieve both increases and decreases in comparison to the initial stiffness. **Figures 17** and **18** show the front and rear wheel dynamic loads when tire stiffness is reduced to 50% of its nominal value. **Figures 19** and **20** present the dynamic wheel loads when tire stiffness is increased to 150% of the nominal value.

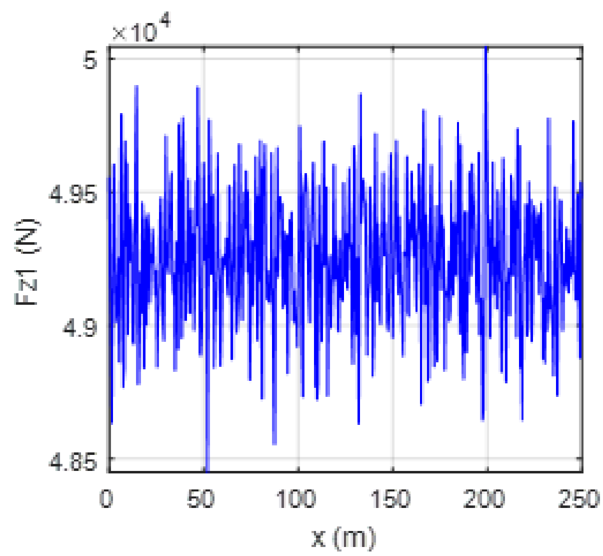

Figure 17. F_{z1}, when the stiffness is reduced to half its original value, the velocity is 90 km/h.

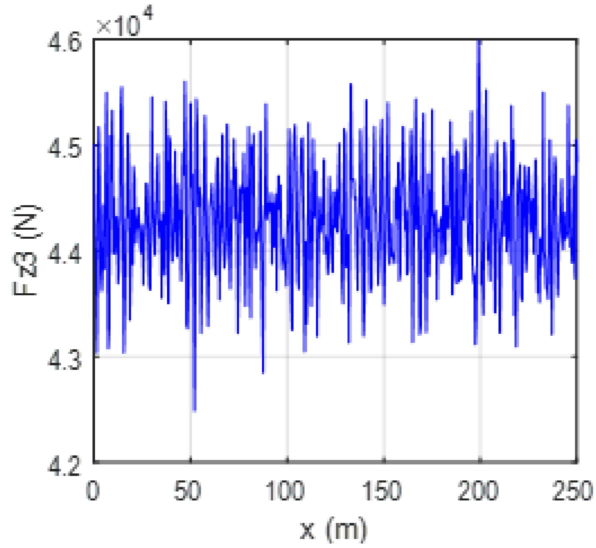

Figure 18. F_{z3}, when the stiffness is reduced to half its original value, the velocity is 90 km/h.

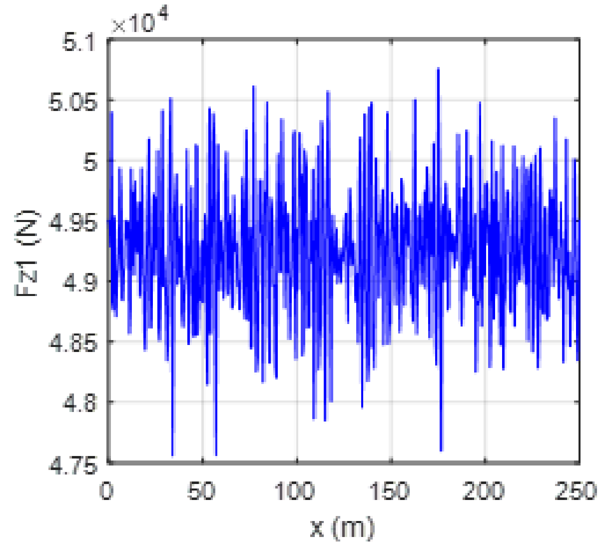

Figure 19. F_{z1}, when the stiffness is increased by 1.5 times, the velocity is 90 km/h.

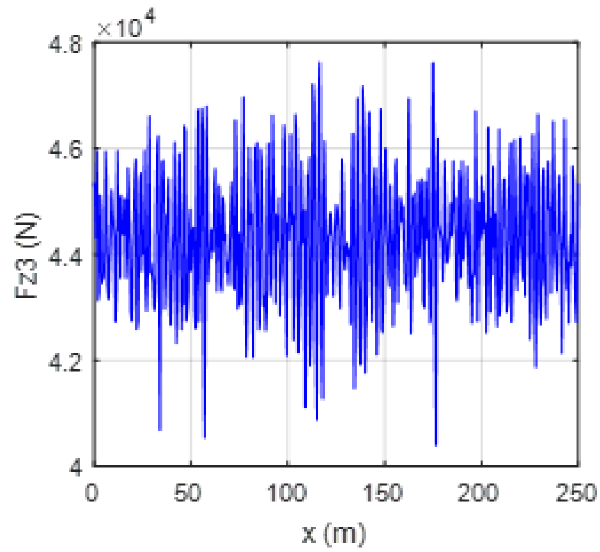

Figure 20. F_{z3}, when the stiffness is increased by 1.5 times, the velocity is 90 km/h.

It is clear from the findings provided in **Figures 21** and **22** that an increase in the stiffness of the tires leads to an increase in the maximum dynamic load value, which is denoted by the symbol F_{zmax}. This is the case even when the speed and the type of road remain the same. On the other hand, when the road conditions remain the same, a rise in the speed of the vehicle also results in an increase in the maximum dynamic load value, which is denoted by the symbol F_{zmax}. To be more specific, the value of F_{z1max} reaches 50,758 N when the tire stiffness is increased by 1.5 times at a speed of 90 km/h, but the value of F_{z3max} is 47,626 N under the same conditions of increased tire stiffness and speed.

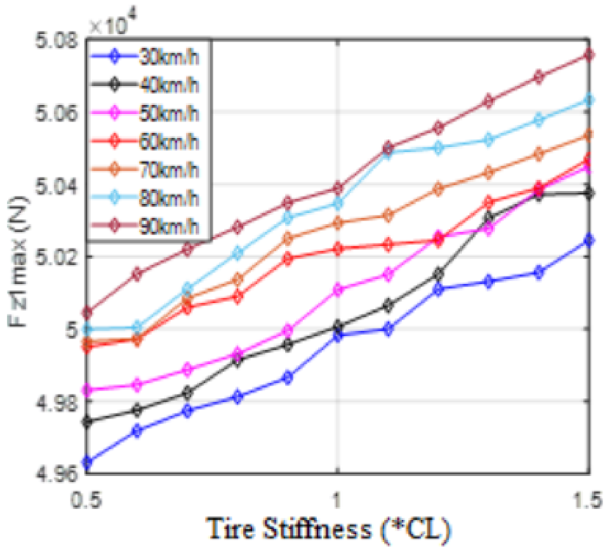

Figure 21. The maximum force (F_{z1max}) on the front wheel occurs within a speed range of 30 to 90 km/h.

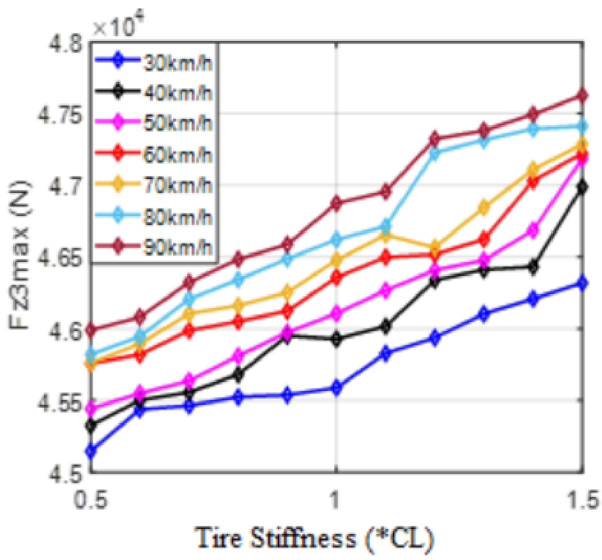

Figure 22. The maximum force (F_{z3max}) on the front wheel occurs within a speed range of 30 to 90 km/h.

The combined effects of vehicle speed and tire stiffness on the maximum wheel loads are summarized in **Table 4**. The road type denoted by the letter B serves as the basis for determining the maximum dynamic load values for both the left front wheel and the left rear wheel separately. While the speed of the vehicle is variable, the stiffness of the tires remains the same. Generally speaking, the maximum dynamic load will grow as the vehicle speed increases on the same type of road, provided that the stiffness does not vary. In this particular example, the maximum dynamic loads that are recorded are as follows when the stiffness is increased by a factor of 1.5: At 30 km/h, the maximum force (F_{z3}) is 46,319 N; at 40 km/h, the maximum force (F_{z3}) is 46,998 N; at 50 km/h, the maximum force (F_{z3}) is 47,186 N; at 60 km/h, the maximum force (F_{z3}) is 47,222 N; at 70 km/h, the maximum force (F_{z3}) is 47,285 N; at 80 km/h, the maximum force (F_{z3}) is 47,412 N; and at 90 km/h, the maximum force (F_{z3}) is 47,494 N. When modifying the tire stiffness in a direction that decreases while maintaining a constant speed on the same type of road, there is a tendency for the maximum dynamic load to drop. An increase in tire stiffness of 1.5 times results in a maximum load (max(F_{z1})) of 50,758 N when the speed of the vehicle is set at v = 90 km/h. It is possible to achieve a maximum load of 50,389 N with the basic tire stiffness. When the stiffness of the tire is lowered by half, on the other hand, the maximum force (F_{z1}) drops to 50,045 N.

Table 4. The maximum dynamic load values at the front wheel (F_{z1max}) and the rear wheel (F_{z3max}) for road type B depend on both the speed and tire stiffness.

On class B								
Tire stiffness	**Dynamic load**	**Velocity (km/h)**						
		30	**40**	**50**	**60**	**70**	**80**	**90**
×0.5C_L	Fz_{1max}	49,631	49,743	49,830	49,951	49,966	49,999	50,045
	Fz_{3max}	45,146	45,324	45,442	45,758	45,760	45,820	45,990
×0.6C_L	Fz_{1max}	49,718	49,776	49,845	49,972	49,973	50,004	50,152
	Fz_{3max}	45,437	45,501	45,549	45,819	45,894	45,946	46,081
×0.7C_L	Fz_{1max}	49,774	49,823	49,887	50,060	50,084	50,110	50,220
	Fz_{3max}	45,463	45,556	45,636	45,987	46,104	46,206	46,322
×0.8C_L	Fz_{1max}	49,813	49,914	49,931	50,090	50,136	50,210	50,281
	Fz_{3max}	45,524	45,680	45,810	46,051	46,162	46,341	46,484
×0.9C_L	Fz_{1max}	49,866	49,957	49,995	50,194	50,250	50,308	50,349
	Fz_{3max}	45,538	45,951	45,974	46,123	46,253	46,487	46,587
C_L	Fz_{1max}	49,982	50,006	50,108	50,221	50,293	50,347	50,389
	Fz_{3max}	45,588	45,927	46,106	46,358	46,477	46,621	46,874
×1.1C_L	Fz_{1max}	50,000	50,065	50,151	50,233	50,315	50,488	50,501
	Fz_{3max}	45,828	46,016	46,267	46,498	46,654	46,713	46,956
×1.2C_L	Fz_{1max}	50,110	50,151	50,254	50,245	50,387	50,501	50,556
	Fz_{3max}	45,937	46,338	46,408	46,518	46,566	47,228	47,322
×1.3C_L	Fz_{1max}	50,131	50,307	50,277	50,350	50,432	50,523	50,630
	Fz_{3max}	46,103	46,411	46,477	46,623	46,846	47,315	47,381
×1.4C_L	Fz_{1max}	50,156	50,372	50,385	50,390	50,484	50,578	50,697
	Fz_{3max}	46,208	46,431	46,686	47,031	47,109	47,394	47,494
×1.5C_L	Fz_{1max}	50,245	50,375	50,449	50,470	50,536	50,634	50,758
	Fz_{3max}	46,319	46,988	47,186	47,222	47,285	47,412	47,626

The results obtained show that the influence of tire stiffness on the dynamic load characteristics of a three-axle truck is nonlinear. The stiffer the tire, the less ability it has to absorb vibrations from the road, so more force is transmitted to the axle and road surface. This explains the increase in the maximum dynamic load and dynamic load coefficient (DLC) at higher stiffness levels. On the contrary, the vibration isolation can be enhanced by reducing the tire stiffness, but large deformation may influence the stability of the vehicle. This trend is also strengthened with the increase in vehicle speed, as the higher excitation frequencies are close to the natural frequencies of the vehicle system and lead to more severe load fluctuations. The current results indicate a more obvious quantitative relationship between the variation of stiffness and dynamic load indicators under ISO 8608 class B conditions than previous studies, which helps to select tire parameters more effectively in practical applications. Sensitivity analysis was carried out to quantify the effect of tire stiffness on the dynamic load response. The results show that increasing the tire stiffness by 1.0–1.5 times leads to an increase in the maximum dynamic load by about 0.7–1.9%, which means a moderate sensitivity of load response to the stiffness change.

4. Conclusion

A multi-body dynamic model of a three-axle truck was developed by the Newton-Euler method. The effect of tire stiffness on the dynamic load characteristics on the road of ISO 8608:2016 class B was studied. Stiffness increases led to a considerable increase in the maximum dynamic load and the dynamic load coefficient, while a decrease in stiffness reduced load amplitudes but might impact stability. In addition, the variation of dynamic load was quantified over a wide range of speeds (30–90 km/h) and stiffness levels (0.5–1.5 times nominal values), thus providing a basis for selecting proper tire parameters to improve vehicle durability and road friendliness.

When a vehicle is traveling at a speed of 90 km/h on a class B road, raising the tire stiffness to 1.5 times the starting level results in a 1.92% increase in the maximum dynamic load on the front axle, while the load on the rear axle climbs by 1.64%. The maximum dynamic load on the front axle is reduced by 0.69% when the tire stiffness is reduced to 0.5 times the initial level at the same speed. On the other hand, the load on the rear axle is reduced by 0.73%, while the maximum dynamic load on the front axle is reduced by 0.69%.

It is essential to choose the appropriate level of tire stiffness for the process. The load capacity, dynamic characteristics, and smoothness of vehicle movement are all impacted by the stiffness of the tires, but the dynamic load of the vehicle is mainly affected by the stiffness of the tires.

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AI use statement: The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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