Hindawi
Shock and Vibration
Volume 2021, Article ID 6641972, 17 pages
https://doi.org/10.1155/2021/6641972

Research Article

Conflict and Sensitivity Analysis of Vehicular Stability Using a Two-State Linear Bicycle Model

Mohamed A. Hassan,[1,2,3] Mohamed A. A. Abdelkareem ,[4,3] Gangfeng Tan ,[1,2] and M. M. Moheyeldein[3]

[1]*School of Automotive Engineering, Wuhan University of Technology, Wuhan 430070, China*
[2]*Suizhou-WUT Industry Research Institute, Suizhou 441300, China*
[3]*Automotive and Tractors Engineering Department, Minia University, El-Minia 61519, Egypt*
[4]*Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong, China*

Correspondence should be addressed to Gangfeng Tan; auto_nova@whut.edu.cn

Received 5 October 2020; Revised 15 January 2021; Accepted 9 February 2021; Published 19 February 2021

Academic Editor: Wahyu Caesarendra

Vehicle parameters and operation conditions play a critical role in vehicular handling and stability. This study aimed to evaluate vehicle stability based on cornering tire stiffness integrated with vehicle parameters. A passenger vehicle is considered in which a two-state linear bicycle model is developed in the Matlab/Simulink. The effect of the vehicle parameters on lateral vehicle stability has been investigated and analyzed. The investigated parameters included CG longitudinal position, wheelbase, and tire cornering stiffness. Furthermore, the effects of load variation and vehicle speed were addressed. Based on a Fishhook steering maneuver, the lateral stability criteria represented in lateral acceleration, yaw rate, vehicle sideslip angle, tire sideslip angles, and the lateral tire force were analyzed. The results demonstrated that the parameters that affect the lateral vehicle stability the most are the cornering stiffness coefficient and the CG longitudinal location. The findings also indicated a positive correlation between vehicle properties and lateral handling and stability.

1. Introduction

The cornering performance of wheeled automobiles is an essential criterion usually associated with vehicular handling and stability [1, 2]. Thus, it is worth investigating the key parameters that affect vehicular stability during the maneuvers. Developing vehicle behavior is quite critical to optimize vehicle handling and comfort in terms of vehicle parameters. In the literature, several studies have mainly focused on investigating the effect of the vehicle inertial parameters such as wheel track, wheelbase, and CG position on vehicle stability without considering the role of the tire characteristics in lateral vehicle dynamics.

1.1. Literature Review. Allen et al. [3] carried out an analysis of the data proposed in the NHTSA Inertia Database [4] to expose the association of yaw/roll moment of inertia and CG height with vehicle properties such as weight, width, length, and height. Consequently, the handling and stability criteria have been studied, showing the influence of vehicle size and speed using a nonlinear maneuvering simulation. The results showed that vehicle properties are strongly influenced by vehicle dimensions, which affect vehicle handling and stability. In [5], the authors introduced a nonlinear bicycle model with a simplified piece-wise linear tire model. The dynamic load transfer behavior was recognized in the proposed model by a developed tuning algorithm for adjusting the tire force based on a measured lateral acceleration. Then, the results were compared with those of the CarSim model simulation with various vehicle maneuvers. The results proved that the proposed bicycle model's trajectory agreed with those obtained by the CarSim model at different vehicle operating conditions. In another study, a simplified 3DOF model was developed and validated to evaluate the influence of the center of gravity location in both vertical and longitudinal directions on the rollover propensity [6]. The results showed that the Static Stability Factor (SSF) is not the only determinate of a vehicle's rollover propensity in which other vehicle properties can considerably influence the rollover propensity, such as weight distribution. In [7], vehicle roll behavior's sensitivity was investigated versus different vehicle parameters, including the track width, CG height, and the wheelbase using a validated nonlinear vehicle model. The correlation between these parameters and the vehicle rollover was obtained, and thus the wheel lift critical velocity was calculated.

Improving vehicle dynamics and stability while driving on roads is a permanent concern and challenge for automotive research and development. Sert and Boyraz [8, 9] have attempted to improve vehicular stability experimentally and theoretically based on the Taguchi technique. They installed antiroll bars with different diameters and leaf springs with two different stiffnesses on the front suspension; therefore, the stability performance was examined. The results showed that a vehicle rollover threshold could be enhanced by increasing both the leaf spring and the antiroll bar's stiffnesses. In another investigation by Ribeiro and Silveira [10], the impact of the main geometric parameters that modify the antiroll bar's stiffness on the vehicular stability and safety based on the Finite Element Method to calculate the antiroll bar stiffness was studied. It was inferred that the vehicles with the antiroll bars are more stable and safe than others without the antiroll bars. Large changes in a vehicle's mass properties can significantly affect its handling characteristics. There are several studies focused on mass property changes and their effects on vehicle handling. Using a mini-van vehicle, Arndt et al. [11] performed on-field tests with four different loading situations under several maneuvers to investigate the real driving vehicle stability. Thereafter, the effects of loading variation on its inertial properties such as the center-of-gravity location and moments of inertia for different vehicles were calculated and then the impact on the stability of the vehicle was measured. Test results proved that the cargo properties (mass and location) remarkedly influenced the vehicle's stability behavior.

It is known that tire characteristics play a significant role in vehicle stability, which is responsible for producing the forces necessary to control the vehicle. The front and rear cornering stiffnesses are used to describe the tires' behavior, particularly the correlation between the lateral tire forces and the tire slip angles. Tire characteristics contribute effectively to the lateral direction stability, particularly tire cornering stiffness. The estimation of the tire cornering stiffness contributes significantly to evaluating the sideslip angle [12] and also regarding improvements in the active steering control system [13]. The tire characteristics terms of the cornering stiffness can be estimated by measuring the vehicle dynamic parameters like lateral accelerations and yaw rate. In reference [14], the authors developed a two-wheeled vehicle model in the CarSim platform to estimate the cornering tire stiffness in which the estimation algorithm was evaluated in terms of both time and frequency domains and concerning experimental data. In another study [15], computer simulation analyses were presented based on a bicycle model to demonstrate the influence of tire characteristics on the handling and stability trends under normal and extreme maneuvering conditions. The obtained results showed that the tire characteristics are a dominant factor in lateral vehicle stability. The effect of the partial/full tire tread separations on the handling characteristics was conducted in [16, 17] with a wide range of vehicle speeds and with different maneuvers. The findings demonstrated that the vehicle's response was seriously affected by the tread separation event as well as the stability depending on the vehicle speed, the location of the separated tread tire, duration, and the shape of the separation event. In recent years, due to the significant advantage in enhancement vehicle dynamics, electric vehicles with multiple electric motors have been attracting attention. Zhang et al. [18] proposed an analytical approach to improve vehicular maneuverability using torque vectoring control. A sensitivity analysis was also introduced to identify the most influencing factors of the additional yaw moment and select the optimal factor values of the electric drive systems during the design stage. In addition, the theoretical results were compared with real experimental data to improve the proposed control under steady and transit state. An optimal torque vectoring control strategy was developed based on a two-level distribution formula to reduce energy consumption and enhance vehicle performance [19]. The simulation results and hardware-in-the-loop experimental results demonstrate that the proposed control strategy can reduce energy consumption while ensuring vehicle stability. A finite-time yaw rate and sideslip angle tracking controller [20] is proposed to improve the maneuverability and vehicle stability by combining an adaptive second-order sliding mode (ASOSM) controller based on the backstepping method to overcome the chattering problem. The proposed algorithm was compared with the First-Order Siding Mode and the Second-Order Sliding Mode in different scenarios to demonstrate its applicability and robustness. An optimal coordinated control integrating active rear-wheel steering (ARS) and direct yaw moment control (DYC) in the form of active drive torque distribution [21] is proposed to enhance vehicular handling and maneuverability of the 4WS and the in-wheel motor drive. The drive torque distribution method and the rear wheel steer strategy were obtained based on the backstepping and optimization method for minimizing tire load and smooth operations. CarSim and Matlab/Simulink simulations were used to demonstrate and verify the effectiveness of the proposed strategy.

1.2. Paper Contribution. Given the literature, most of the conducted studies have mainly focused on the vehicle parameters' effect, including the vehicle inertial properties on the vehicular stability and its sensitivity to each parameter, while others were only limited to the investigation of the tire characteristics' influences on the lateral vehicle dynamics. In this paper, comprehensive parametrical conflict analyses are introduced to evaluate the vehicular lateral stability terms of the lateral acceleration, yaw rate, vehicle sideslip angle, tire sideslip angles, and the lateral tire force. The parametrical conflict analysis includes the longitudinal position of the vehicle CG, wheelbase, and tire cornering stiffness. Furthermore, the vehicular lateral stability is also evaluated concerning the load variation and the vehicle speed. This investigation tends to define the conflict and trade-off between the vehicle stability responses for different simulation conditions.

2. Bicycle Single Track Model

This paper presents the two-state linear bicycle model to describe the vehicular lateral dynamics during the parametrical conflict simulations. In the modeling, the left and right vehicle tires were assumed to have the same characteristics, and therefore it could reduce the four-wheeled vehicles to an equivalent two-wheeled vehicle model. It is also assumed that the roll motion and the longitudinal tire slip are neglected. Furthermore, the pitch motion, which causes longitudinal weight transfer, is neglected since longitudinal acceleration is not considered in the presented model. Figure 1 introduces the bicycle model for a passenger vehicle in which only the front wheel is steerable. The lateral dynamic model is presented in terms of the following state variables; the lateral velocity (v_y), yaw rate (r), and the lateral tire forces (F_{y_f}), and (F_{y_r}) for front and rear, respectively. The equation of motion of the proposed model can be directly derived by applying the force equilibrium along the y-axis and taking the moment around the center of gravity corresponding to the z-axis.

Firstly, the vehicle's lateral motion is obtained as follows:

$$M\left(\dot{v}_y + r v_x\right) = F_{y_f} + F_{y_r}. \tag{1}$$

Secondly, the vehicle's yaw motion is obtained as appended below:

$$I_z \dot{r} = aF_{y_f} - bF_{y_r}. \tag{2}$$

From equations (1) and (2), it can be seen that the vehicle lateral force and the yaw moment only depend on the front and rear wheel's lateral forces. The tire forces are defined within equations of the linear tire model, which are functions of the wheels' sideslip angles $\alpha_f$and α_f.

$$F_{y_f} = k_{\alpha f}\alpha_f, \tag{3}$$

$$F_{y_r} = k_{\alpha r}\alpha_r. \tag{4}$$

The tire position and the steering angle have a significant impact on the sideslip angles of tires. Therefore, the sideslip angle per tire could be calculated as follows:

$$\alpha_f = \beta + \frac{ar}{v_x} - \delta_f, \tag{5}$$

$$\alpha_r = \beta - \frac{br}{v_x}. \tag{6}$$

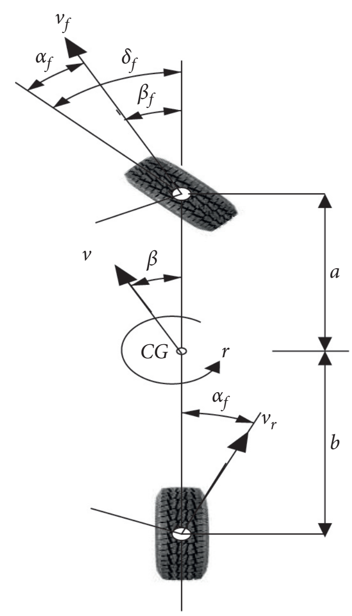


Figure 1: Linear bicycle model.

Substituting by Equations (3)-(6) in equations (1) and (2), the state-space representation is presented as follows:

$$\begin{bmatrix} \dot{v}_y \\ \dot{r} \end{bmatrix} = \begin{bmatrix} -\dfrac{k_{\alpha f} + k_{\alpha r}}{M v_x} & \dfrac{-ak_{\alpha f} + bk_{\alpha r}}{M v_x} - v_x \\ -\dfrac{ak_{\alpha f} - bk_{\alpha_r}}{I_z v_x} & -\dfrac{a^2 k_{\alpha f} - b^2 k_{\alpha_r}}{I_z v_x} \end{bmatrix} \begin{bmatrix} v_y \\ r \end{bmatrix} + \begin{bmatrix} \dfrac{k_{\alpha f}}{M} \\ \dfrac{k_{\alpha r}}{I_z} \end{bmatrix} \alpha_f, \tag{7}$$

where v_x is the forward vehicle speed, v_y is the lateral vehicle speed, r is the yaw rate, M is the vehicle mass, I_Z is the yaw moment of inertia, and $k_{\alpha f}$ and $k_{\alpha r}$ are the front and rear cornering stiffnesses. δ_f donates for the front wheel steering angle, whereas a and b are the distances from the vehicle center of gravity to the front and rear axles, respectively.

In this investigation, the vehicular stability sensitivity analysis is conducted based on a bicycle model as described above. The significant reason for using the single-track model (bicycle model) is that it is the most common model for analyzing the vehicle's lateral dynamics [22, 23]. Besides, many studies have proven that the response of a complex model such as the six degrees of freedom (6 DOF) model and a simple (2 DOF) model remains close to each under typical operating conditions [24]. Despite its simplicity, the two-degree-of-freedom model can be very useful in demonstrating the interaction of major parameters such as tire properties, inertia properties, mass center location, wheelbase, and forward speed. In this paper, the lateral vehicle stability is studied considering the variation of the vehicle design parameters and the operation factors. The investigated parameters include essential vehicle properties such as cornering tire stiffness, CG longitudinal, wheelbase, vehicle speed, and payload condition.

3. Simulation Assessment

The Matlab/Simulink simulation platform was used to implement the vehicle's linear bicycle model through a steady-state cornering based on the aforementioned modeling and equations. This model can be used to evaluate both the parametrical conflict and the sensitivity of vehicular stability and handling. The simulation analysis was carried out for a Fishhook 1a steering maneuver as referred to in Figure 2. During the simulations, the model parameters used in the conflict and sensitivity analyses are presented in Table 1. Furthermore, the vehicle speed was kept constant at 20 m/s. Concerning the conflict and sensitivity analyses, the vehicle parameters were varied within chosen limits to explore their correlation versus the vehicle stability responses.

In this paper, the parametric sensitivity analysis aims to study the vehicular lateral stability under extreme conditions, including high velocity and low adhesive roads with low cornering stiffnesses. This study also identifies the most influential parameters that affect lateral stability, which gives a complete view of the vehicle lateral dynamics. The conflict and parametric sensitivity investigations allow for achieving better lateral vehicle dynamics under extreme driving conditions. To ensure the model validity first, we compare our model simulation results with relevant published papers [7, 25, 26]. In typical situations, the vehicle offers high cornering stiffnesses to ensure limited sideslip angles. Our study carried out conflict and sensitivity simulations to study and investigate how the car behaves in terms of lateral and rollover stabilities in extreme conditions. The proposed car model was simulated, as shown in Figure 3, for both high and low cornering stiffness situations with respect to the CG location and the vehicle speed variations. Figure 3 shows the front and rear sideslip angles that are plotted and compared for normal and extreme cases (two types of tires: low and high tire cornering stiffnesses). As shown in Figure 3(a), the sideslip RMS decreases significantly with an increase in the tire cornering stiffness. The minimum sideslip RMS is achieved when the CG position is closer to the front axle and vice versa. We can see from Figure 3(a) that when a high cornering stiffness tire is considered, the sideslip angle remained under 20 degrees. Otherwise, the sideslip angle increased significantly to reach 55 degrees when using a low cornering stiffness tire. At the nominal GC location, the front/rear sideslip angles are nearly 10 and 20 degrees for high and low tire cornering stiffness cases, respectively. In Figure 3(b), the correlation of the sideslip RMS with the vehicle speed at high and low tire cornering stiffness cases is given. Decreasing the vehicle speed gives a lower sideslip angle, especially at high cornering stiffness values. At 15 m/s driving speed, the time-domain sideslip angles are plotted to illustrate the effect of the high and low tire cornering stiffness cases. The results indicated a significant increase in the sideslip with low cornering stiffness, especially at high

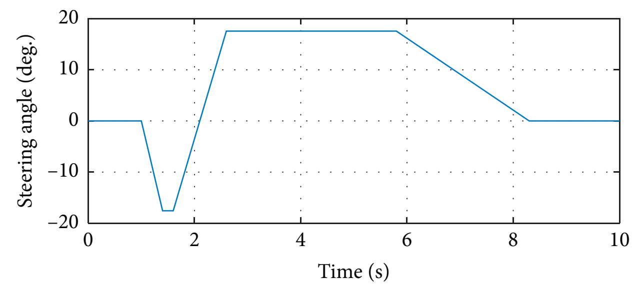


Figure 2: Steering angle input at wheels for the Fishhook 1a maneuver.

Table 1: Parameters and values of the linear bicycle model.

Parameter	Symbol	Value
Vehicle mass	M	1690 kg
Yawing moment of inertia	I_Z	2940 kg
Front tire cornering stiffness	$K_{\alpha f}$	60000 N/rad
Rear tire cornering stiffness	$K_{\alpha r}$	60000 N/rad
Vehicle speed	v_x	20 m/s
The front axle distance referenced form CG	a	1.3 m
The rear axle distance referenced from CG	b	1.38 m

vehicle speeds. Our car model's simulation results are in considerable agreement with those obtained in [26–28]. This confirms and supports the validity of the proposed model and the parameters used in our study.

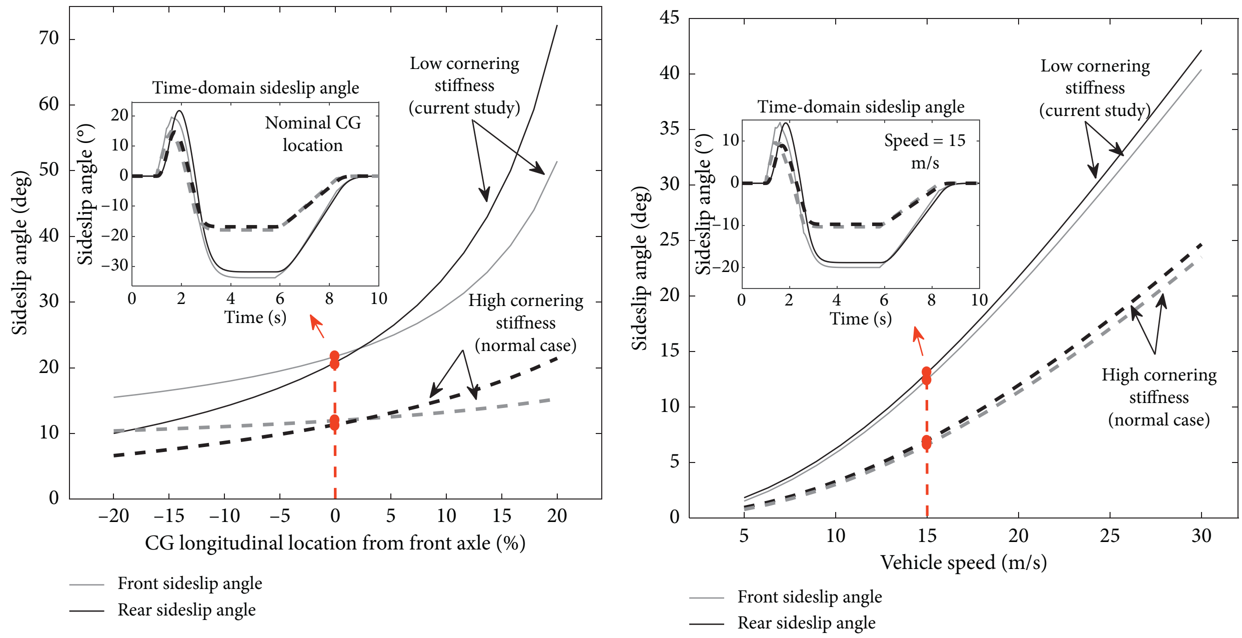
4. Results and Discussion

During the conflict and sensitivity simulations, the lateral acceleration, yaw rate, sideslip angle, tire lateral forces, and the corresponding tire sideslip responses are investigated based on a two-state linear bicycle model as derived in Section 2. Those vehicular lateral stability responses have been evaluated in complete parametric simulations, including the front and rear tire cornering stiffnesses, payload percentage, vehicle center of gravity longitudinal location, wheelbase length, and vehicle speed. In this paper, the time histories of vehicular lateral stability are recorded with parameter variation. Besides, the root-mean-square (RMS) index is calculated as

$$RMS = \sqrt{\frac{1}{T}\int_0^T u(t)^2 dt}, \tag{8}$$

where $u(t)$ is the response time signal such as lateral acceleration, yaw rate, front/rear lateral force, and the sideslip angles. T is the total number of samples.

The RMS values are the most common index for evaluating vehicle dynamics, handling, and vehicle stability. In lateral and vertical motions, the RMS provides a time-



(a) (b)

Figure 3: Sideslip angle responses for two different cornering tire stiffness values as a function of (a) CG longitudinal position from the front axle and (b) vehicle speed.

averaged value that can be considered a useful metric in evaluating vehicle handling and discomfort. Many studies evaluated vehicular ride comfort and lateral stability based on the RMS metric [29–37].

4.1. Influence of the Cornering Stiffness Coefficient. Knowingly, tire characteristics are critical in terms of vehicle handling performance. The front and rear cornering stiffness coefficients are used to describe the tires' behavior. In this manner, several cases are proposed through the simulations to evaluate the effect of the cornering stiffness coefficient on both stability and handling.

Case A: in this case, the front cornering stiffness is varied by ± 30% from its nominal value, and the rear cornering stiffness coefficient is held constant. It is worth mentioning that the sum of the front and rear cornering stiffnesses is not constant and only depends on the percent of change in the front cornering stiffness. Accordingly, the distribution rate ($K_{\alpha_f}/K_{\alpha_r}$) for the front/rear cornering stiffnesses is ranged from 0.7 to 1.3.

Case B: herein this case, the front cornering stiffness coefficient is kept constant while the rear cornering stiffness is varied by ± 30%, referenced from its nominal value (60 kN/rad). The sum of the front and rear cornering stiffnesses only depends on the percent of change in the rear cornering stiffness. The distribution rate ($K_{\alpha_f}/K_{\alpha_r}$) is changed from 1.4 to 0.75.

Case C: in this case, both the front and rear cornering stiffness coefficients are varied simultaneously while their sum is kept constant (150 kN/rad). In this case, the distribution rate ($K_{\alpha_f}/K_{\alpha_r}$) is ranged from 0.5 to 1.5.

In this section, the vehicular stability responses are investigated for each case, and then a comparison between them is carried out. Firstly, the performance criteria of the vehicle handling and stability by Case A are described in Figures 4(a) and 4(b). The correlations between the front cornering stiffness coefficient (±30% referenced from its nominal value) and the lateral acceleration, yaw rate, and vehicle sideslip angle are depicted in Figure 4(b). From the graph, it can be seen that there is a significant correlation between the front cornering stiffness and these responses. The lateral acceleration, yaw rate, and vehicle sideslip angle decreased with lower front cornering tire stiffness. It is also noticeable that the yaw rate and vehicle sideslip angle trends present an approximately equal percentage of change, being 43% and 70%, versus the decrease and the increase of the cornering stiffness coefficient, respectively. While the lateral acceleration increased by 38% and decrease by 32% for the ±30% front cornering stiffness variations. This inferred that the whole responses are highly sensitive to the change in the front cornering stiffness coefficient.

Looking at Figure 4(b), the RMS trends of the front and rear lateral forces with corresponding tire sideslip angles are plotted versus the front cornering stiffness variation. The most interesting aspect of this graph is that the growth of the front and rear lateral forces as well as the front and rear tire sideslip angles at higher rates of the front cornering stiffness. On the other hand, the RMS of the front and rear lateral forces and its corresponding tire sideslip angles decreased at the lowest cornering stiffness rates. Results showed that the minimum RMS values of the sideslip angle for both the front and rear tires are located at the lowest cornering stiffness coefficient (−30% of the nominal value) being 17.5 and 11.8

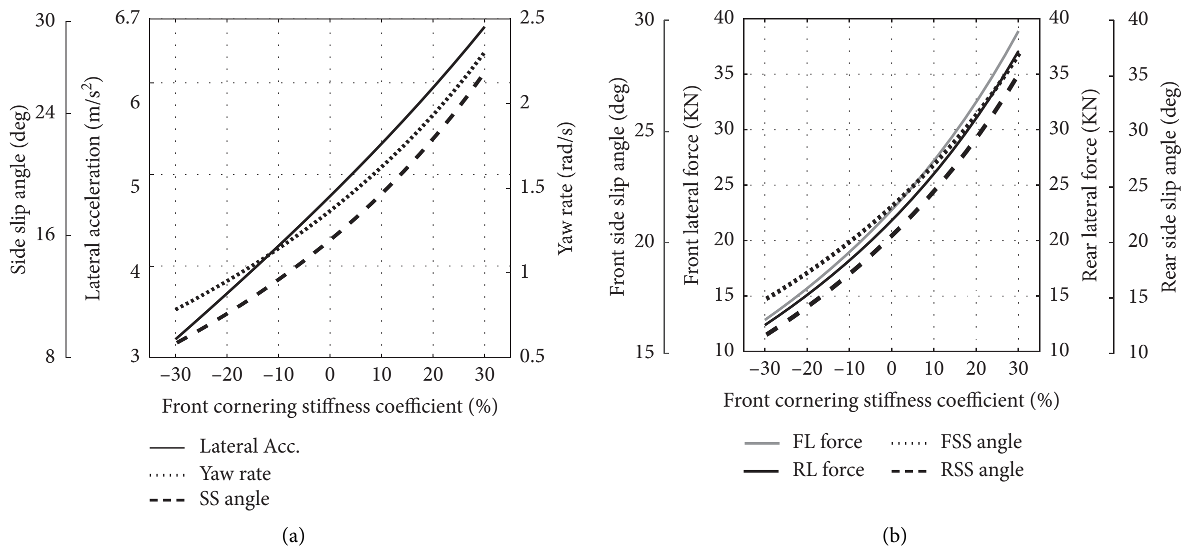


Figure 4: Conflict analysis of the lateral dynamics as a function of the front cornering stiffness: (a) lateral acceleration, yaw rate, and vehicle slip angle; (b) front and rear lateral forces, and tire sideslip angles.

degrees, respectively. While at the highest cornering stiffness, the RMS values of the front and rear tire sideslip angles were 28 and 35 degrees, respectively. The reason why the front tire sideslip angle was lower than that of the rear tire at the lowest cornering stiffness is that the rear tire cornering stiffness is higher than that of the front tire since the tire sideslip angle has mainly functioned of the cornering stiffness as their lateral forces are almost equal at lower cornering stiffnesses. Conversely, at the highest front cornering stiffness, while the rear tire cornering stiffness is fixed, it is noted that the front slip angle was lower than that of the rear wheel because the cornering stiffness corresponding to the front tire was higher than that of the rear tire.

The influence of the rear cornering stiffness variation on the lateral acceleration, yaw rate, vehicle sideslip angle, lateral forces, and sideslip angles of the front and rear tires is displayed in Figures 5(a) and 5(b) according to the scenario presented in Case B. As shown in Figure 5(a), there is an inverse interdependence between the rear cornering stiffness and the vehicle stability responses. Interestingly, when the rear cornering stiffness declined by 30% of its nominal value, the lateral acceleration markedly grew by nearly 1.4 times its nominal value while the yaw rate increased by 2 times. Moreover, the vehicle sideslip angle increased sharply by 4 times compared to the nominal rear cornering stiffness. By contrast, for a 30% increase in the rear tire cornering stiffness, there has been a slight decrease in the lateral acceleration, yaw rate, and vehicle sideslip angle. It is now understood that the reduction in the rear cornering stiffness is associated with a significant effect on the lateral acceleration, yaw rate, and vehicle sideslip angle. While with the excessive increase in the rear cornering stiffness, these responses were considerably different, being almost constant. These results are of great interest in terms of design aspects, including the tire characteristics. The correlational analysis of the front/rear lateral forces and the tire sideslip angles with the rear cornering stiffness variation is described in Figure 5(b). The results indicated an inverse relationship between the lateral force and the tire slip angle to the variation in the rear cornering stiffness. Figure 5(b) illustrates that both the lateral force and the slip angle showed a downward trend when the rear cornering stiffness was raised. The responses improved considerably while increasing the cornering stiffness value, which infers better vehicle linear handling performance. The same correlation is confirmed in [27, 38].

Based on Case C, the correlation between the distribution rate of the cornering stiffnesses ($K_{\alpha_f}/K_{\alpha_r}$) and the stability criteria are introduced in Figures 6(a) and 6(b). Figure 6(a) shows that clear downward trends of the lateral acceleration, yaw rate, and sideslip angle are observed with the decline of the cornering stiffness distribution rate. On the contrary, the proposed responses have risen with the increase in the cornering stiffness distribution rate. According to the correlation between the distribution rate and the lateral forces and sideslip angles of the front and rear tires (Figure 6(b)), it can be seen that the increase in the distribution rate is accompanied by an increase in both the lateral forces and sideslip angles for both tires. Comparing with the previous findings in Figure 6(a), it is demonstrated that the lower cornering stiffness distribution rates provide better vehicular stabilities. Conversely, the higher distribution rates gave the worst handling performance.

Overall, the proposed cases' findings support the view that there is a significant positive correlation between the variation of the cornering stiffness coefficient and the vehicular lateral stability criteria. It is clear that the lower distribution rate of the cornering stiffness coefficient provides better lateral stability and handling for the aforementioned suggested cases. Conversely, the higher distribution rate causes the worst stability criteria. However, there is a discrepancy between the improvement and the deterioration percentages in the lateral stability responses in the proposed cases, which are clarified in Figures 6(a) and 6(b).

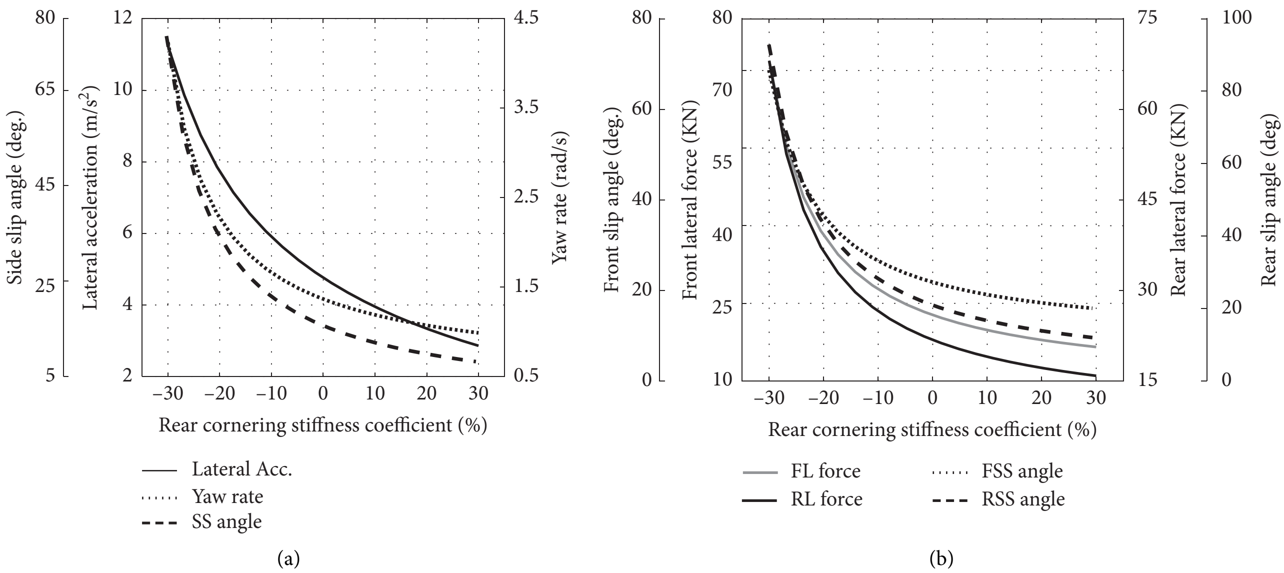


Figure 5: Conflict analysis of the lateral dynamics as a function of the rear cornering stiffness: (a) lateral acceleration, yaw rate, and vehicle slip angle; (b) front and rear lateral forces, and tire sideslip angles.

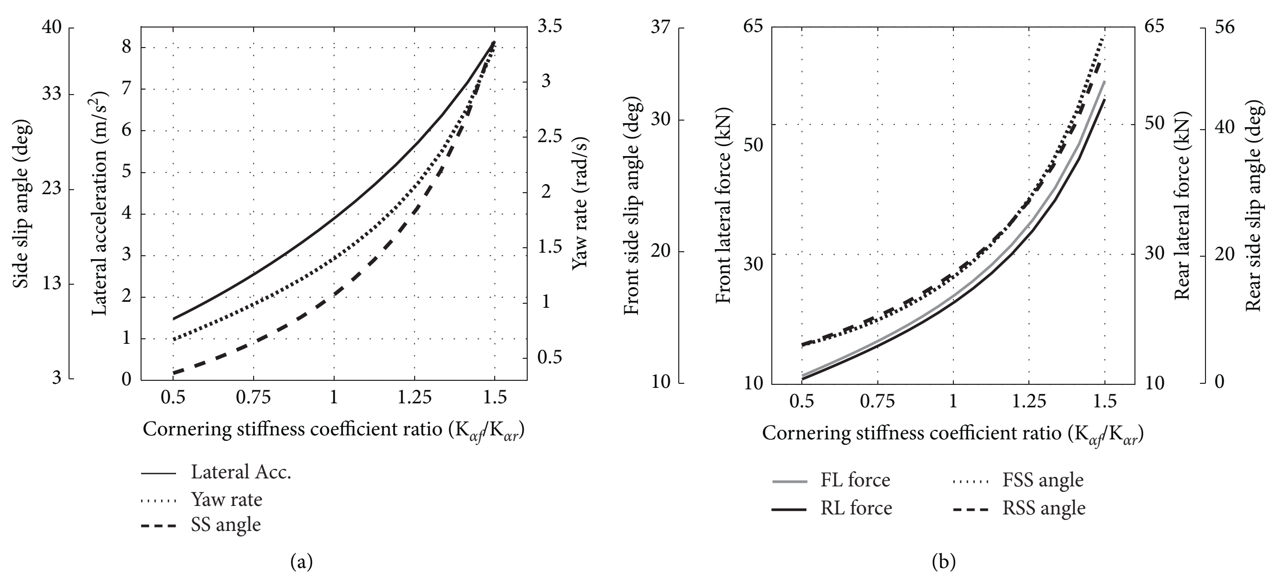


Figure 6: Conflict analysis of the lateral dynamics as a function of the distribution rate of the cornering stiffness coefficient: (a) lateral acceleration, yaw rate, and vehicle slip angle; (b) front and rear lateral forces and tire sideslip angles.

To achieve impartiality in comparing the three suggested cases, the distribution rate has been fixed during this investigation. Hence, the lowest and the highest distribution rates of 0.75 and 1.3 were selected in the three cases, as explained in Table 2. According to the data shown in Figures 7(a) and 7(b), it is observed that the maximum improvement percentage in the lateral stability was found at the lower distribution rate (0.75) for Case C, which is higher than the improvement percentage in the others (Cases A and B). On the other hand, Case C also provides the lowest deterioration percentages of the lateral stability than others (Cases A and B) at a higher distribution rate (1.3).

The suggested cases demonstrate the need for better design strategies for identifying the front and the rear cornering stiffness coefficients' values. Even though the distribution rate was fixed in these three cases, there is a disparity in the improvement and the deterioration percentages. Furthermore, the enhancement in the stability criteria not only depends on the distribution rate but also on the summation of the front and the rear cornering stiffness values.

4.2. Influence of the Payload Variation. The vehicle weight is generally seen as a factor strongly related to its dynamic performance. The great changes in a vehicle's load can

Table 2: Simulation conditions under lower and higher fixed cornering stiffness distribution rates.

Condition	Cornering stiffness coefficients (kN/m)		
	Front cornering stiffness	Rear cornering stiffness	Total stiffness
Lower distribution rate $(K_{\alpha_f}/K_{\alpha_r}) = 0.75$			
Case A	45	60	105
Case B	60	80	140
Case C	64.7	85.3	150
Lower distribution rate $(K_{\alpha_f}/K_{\alpha_r}) = 1.3$			
Case A	80	60	140
Case B	60	45	105
Case C	85.8	64.2	150

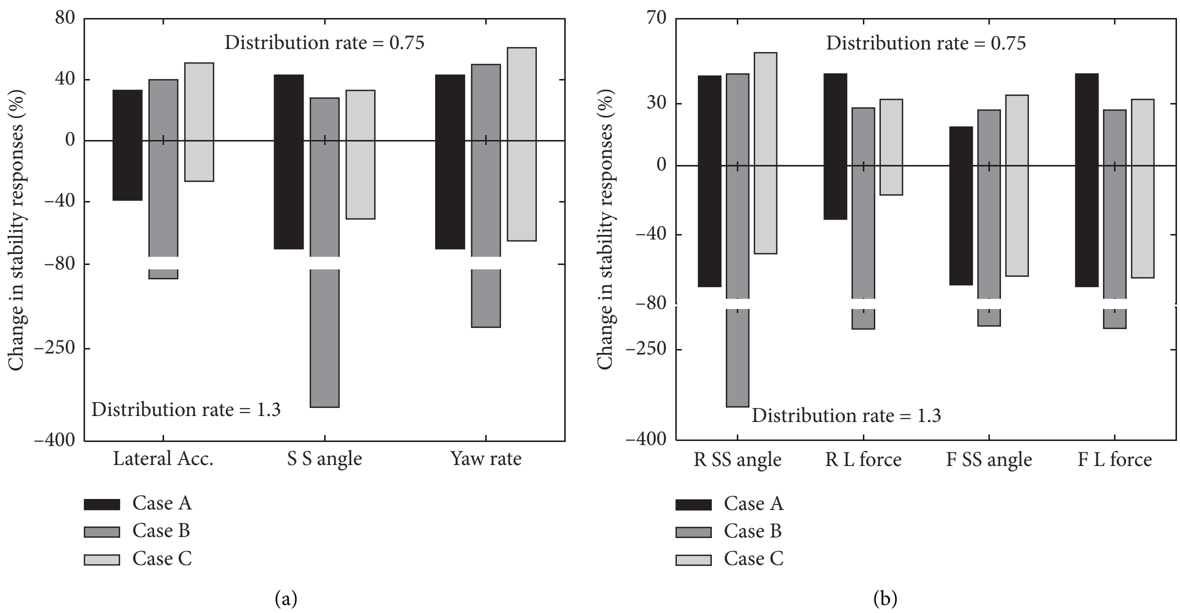


Figure 7: Improvement and deterioration of the lateral dynamics at 0.7 and 1.3 distribution rate: (a) lateral acceleration, yaw rate, and vehicle slip angle, (b) front and rear lateral forces and tire sideslip angles.

significantly affect its handling characteristics, with the typical vehicle drivers probably not realizing the danger that leads to severe consequences not only for them but also to others. In this section, the simulations explore the relationship between the change in the passenger and the cargo loads, and the lateral vehicle dynamics. Thus, the lateral acceleration, yaw rate, vehicle sideslip angle, tire lateral forces, and tire slip angles are evaluated with payload variation.

Figure 8(a) reveals the lateral acceleration, yaw rate, and the vehicle sideslip angle correlations with vehicle payload variation. Adding load usually causes a change in the vehicle moment of inertia; however, the simulations were conducted in this section assuming that the added load is only considered at the vehicle center of gravity. Therefore, the moment of inertia is not adjusted. Based on the simulations, it is reported that there is an increase in both the lateral acceleration and the vehicle sideslip angle trends with the increase of vehicle cargo. By contrast, there is no significant disparity found between the payload variation and the yaw rate. There is no significant correlation between the yaw rate and the applied payload because the vehicle load mass was varied, but its yaw moment of inertia remains constant. According to these data, it can be concluded that when the vehicle load increases by 30% of the vehicle curb weight, the lateral acceleration and the vehicle sideslip angle approximately increased by the same percentage, being 29.8%. Finally, the outcome of the analysis has found an interesting correlation between the vehicle mass and both the lateral acceleration and the sideslip angle during cornering. These results are in agreement with those obtained by [39, 40].

The relation between the lateral force and the sideslip angle versus the vehicle payload variation is shown in Figure 8(b). It is observed that both the tire lateral force and the sideslip angle are varied upward with the addition of the payload. This means that when the vertical load on a tire increased, the lateral and the sideslip angle also increased.

4.3. Influence of the CG Longitudinal Position. This section evaluates the vehicle stability responses, such as lateral acceleration, yaw motion, sideslip angle, and the tire lateral forces and the sideslip angles, concerning the shift in the

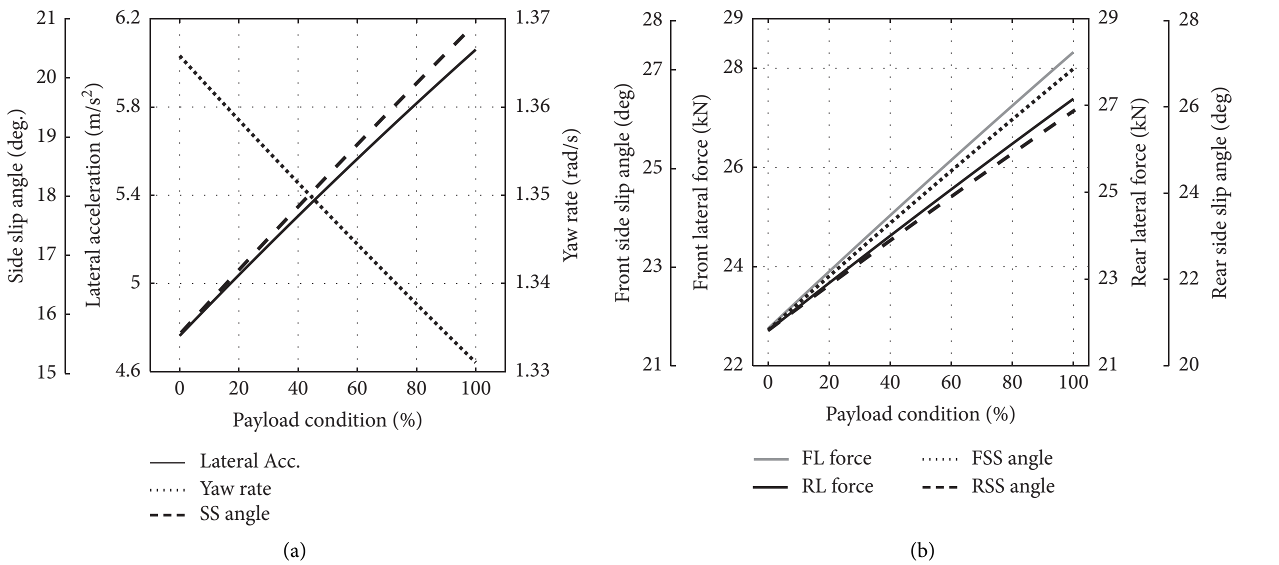


Figure 8: Conflict analysis of the lateral dynamics as a function of the loading conditions: (a) lateral acceleration, yaw rate, and vehicle slip angle; (b) front and rear lateral forces and tire sideslip angles.

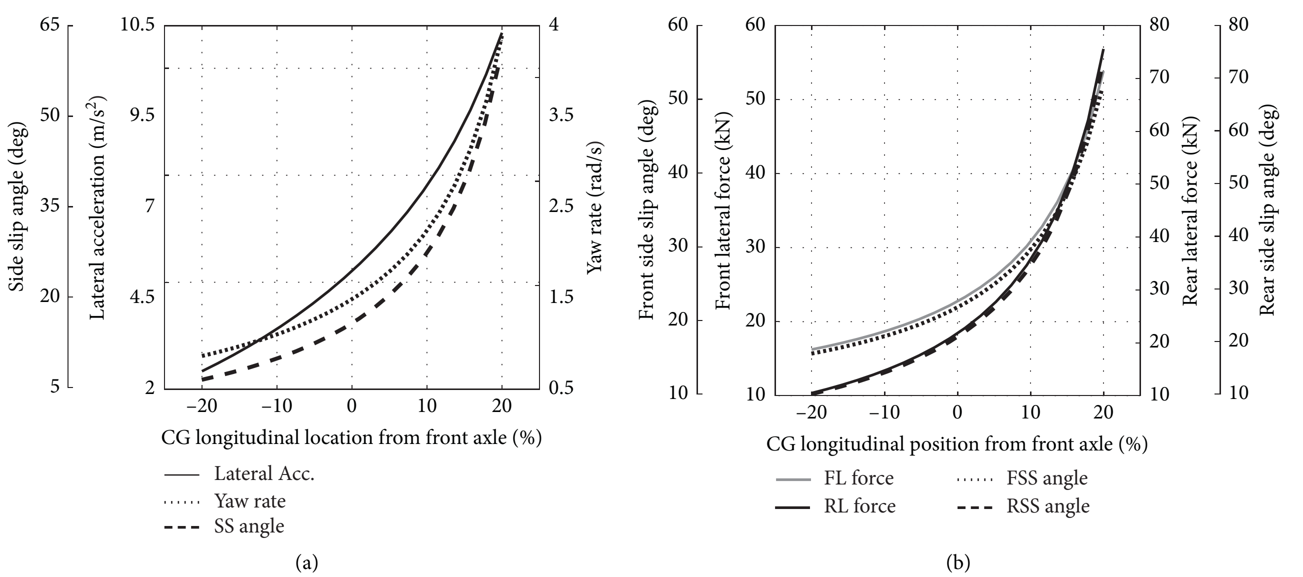


Figure 9: Conflict analysis of the lateral dynamics as a function of longitudinal CG position: (a) lateral acceleration, yaw rate, and vehicle slip angle; (b) front and rear lateral forces and tire sideslip angles.

longitudinal position of the vehicle center of gravity. The CG location is shifted referenced from both the front and the rear axles while the wheelbase is held constant. Here, the center of gravity shifting was varied by ±20% from its nominal configuration. Where both the front and the rear tires cornering stiffness coefficients were identical, the effects on the presented responses as a result of changing the CG location are isolated from other factors. In this manner, Figure 9(a) illustrates the impact of moving the vehicle CG location in the longitudinal direction on the lateral acceleration, yaw rate, and the vehicle sideslip angle. Figure 9(a) infers that when the center of gravity is shifted to the front axle by 20%, the lateral acceleration, yaw rate, and sideslip angle are reduced compared to the base model. Contrary to earlier, moving the CG backward to the rear of the vehicle has a more dramatic effect on the lateral acceleration and the sideslip angle. The previous analysis showed that more vehicular stability is achieved when the center of gravity is closer to the front axle rather than the rear axle. When the CG is closer to the front axle, the front sideslip angle becomes larger than the rear sideslip angle, and thus the vehicle is headed off in the direction of the side force leading to more vehicle stability. In the case of constant steering angle, the positive yaw will turn the front of the vehicle toward the outside of the original path, thereby increasing the turning radius and reducing the centrifugal force. In contrast, if the

CG is closer to the rear axle, the rear slip angle becomes larger than the front sideslip angle, and the vehicle is turned against the direction of the side force, making the rear of the car move outward from the original path, thereby decreasing the turning radius and increasing the centrifugal force, which requires greater correction. Thus, the vehicle may lose its stability before the desired correction before it spins.

Figure 9(b) shows the lateral forces on both the front and the rear tires, and the corresponding tire slip angles with the center of gravity location variation by ±20% according to the original position. It can be observed that moving the center of gravity toward the front axle causes a decrease in the tire sideslip angle and reduces the lateral tire force. This is because of the increase of the load on the front wheel when the center of gravity is moved closer to the front axle, and thereby the front tire reaches the grip limit before the rear tire. This prevents further enhancement of the lateral acceleration, rendering the driver unable to keep the vehicle in the intended path; subsequently, the car tends to have a different path with a larger radius. The car in this situation approaches dynamical stability, although the lateral acceleration trend showed no noticeable increase. Conversely, suppose the center of gravity is shifted back to the rear wheel, in that case, this leads the rear tires to reach the grip limit earlier than the front tires, forcing the vehicle to become critically oversteered and thereby unstable. This can be indicated as the phenomena of drifting.

4.4. Influence of the Wheelbase Length. The impact of the wheelbase on the vehicle's dynamic behavior, mainly the lateral stability and handling, is studied by changing the wheelbase length with a fixed ratio of the CG location from the front and the rear axles. Accordingly, the simulations were done for a Fishhook steering input at an entrance speed of 20 m/s.

Vehicle stability characteristics represented in the lateral acceleration, yaw rate, vehicle sideslip angle, the front/rear lateral tire forces, and slip angles were studied versus a ±30% variation in the wheelbase length referenced from the default setting, as revealed in Figures 10(a) and 10(b). The aforementioned vehicle stability responses have risen with the wheelbase's decrease, where the maximum RMS values of the proposed stability characteristics are achieved for a 30% decrease in the wheelbase. On the other hand, with the increase of the wheelbase (+30% of the nominal value), the minimum trends of the proposed vehicle stability characteristics were obtained. It is concluded that vehicles with longer wheelbases may provide better overall stability performances than those having a comparatively short wheelbase.

4.5. Influence of Vehicle Speed. One of the critical parameters that have a significant influence on the vehicle stability during cornering is vehicle speed. Figures 11(a) and 11(b) illustrate the vehicle's responses (lateral acceleration, sideslip angle, yaw rate, front and rear tire lateral forces, and sideslip angles) during the fishhook maneuver with a change in the entrance vehicle speed. The vehicle speed was ranged from 5 to 30 m/s. Figure 11(a) shows a clear upward trend of the lateral acceleration, yaw rate, and sideslip angle with the increase of the vehicle speed. It is known that the total lateral force from both tires is varied quadratically with speed, which is proved within Figure 11(b). Subsequently, the vehicle responses at a lower driving speed remained stable than higher speeds because the produced lateral force at the lower driving speeds is not sufficient to induce rollover.

This investigation has indicated potential associations between the change of the selected parameters and the vehicular stability criterion, where several important points are concluded in this section. Figure 12 summarizes the selected parameters' effect (tire cornering stiffness, wheelbase, CG longitudinal position, vehicle speed, and payload) on the lateral stability responses during cornering (lateral acceleration, yaw rate, sideslip angle, and lateral tire forces). From Figure 12, it is concluded that the most parameters that affect the lateral vehicle stability are the rear cornering stiffness and the CG longitudinal location, while the speed of the vehicle also has a noticeable effect as well. The decrease of the rear cornering stiffness has a remarked effect compared to the rear cornering stiffness increase with the same percentage where, and this phenomenon is visible in Figure 12. This may be due to the increase in the distribution rate ($K_{\alpha_f}/K_{\alpha_r}$) and thereby a consequent deterioration of the vehicle's stability. It is also noted that the vehicle stability correlated strongly to the variation of the CG location with the same correlation level of the rear cornering stiffness, especially in the case of the rear lateral force, as shown in Figure 12(f). One of the major findings is that moving the center of gravity in the backward direction causes a higher degradation percentage in the lateral vehicle stability than the improvement percentage achieved by shifting the CG in the forward direction. The vehicle speed comes in the third rank affecting the vehicle's stability, particularly in terms of the lateral acceleration in which the lateral acceleration depends highly on the driving speed, as referred to in Figure 12(a). According to the conditions mentioned in this study, the wheelbase and the payload weakly influenced the vehicle stability responses compared to the other parameters, particularly in the lateral acceleration and yaw rate, respectively, as shown in Figures 12(a) and 12(b).

4.6. Parametric Sensitivity Analysis. A parametric sensitivity correlation analysis is proposed to understand the vehicle parameters' sensitivity versus the vehicular stability criteria. The sensitivity analysis investigates how the variation of the vehicle parameters affects the stability responses. In this manner, the vehicle stability responses' sensitivity was analyzed using the fishhook maneuver versus the front and the rear cornering stiffnesses, CG longitudinal position, wheelbase length, vehicle speed, and payload. Figure 12 displays the correlation sensitivity of the aforementioned parameters on the proposed vehicular stability criteria. In Figure 12(a), the correlation sensitivity results showed that the lateral acceleration sensitivity correlated remarkedly to the vehicle parameters but mostly to the rear cornering coefficient.

For the lower rear cornering stiffnesses, the lateral acceleration's sensitivity to the small change in the rear cornering stiffnesses is higher than that when the higher rear cornering stiffnesses were considered. However, the increase in the rear

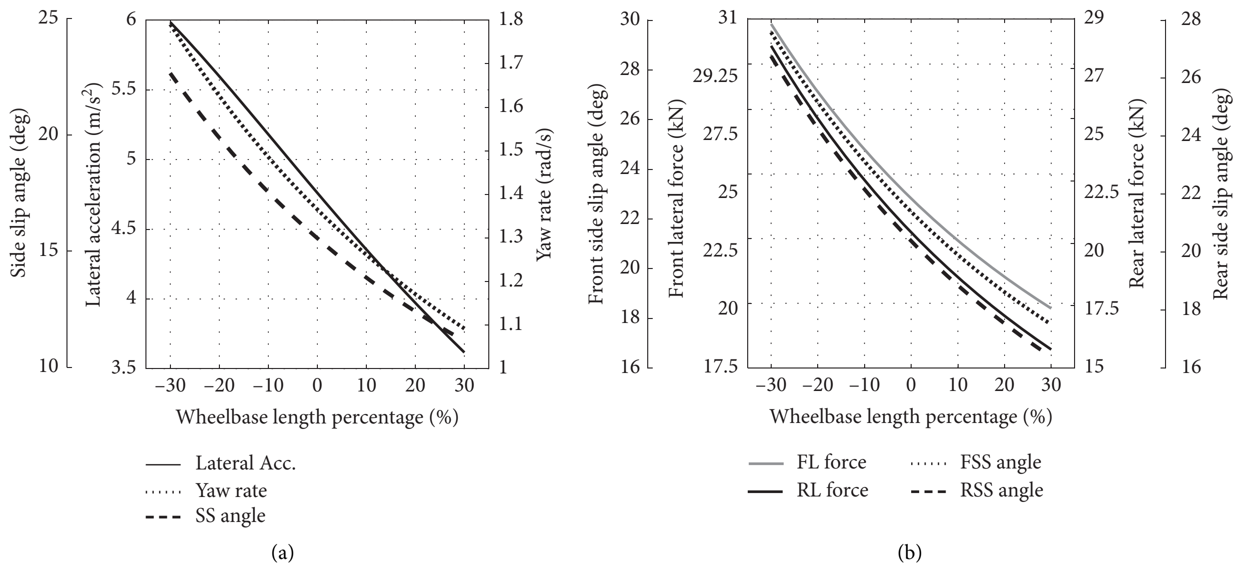


Figure 10: Conflict analysis of the lateral dynamics as a function of wheelbase length: (a) lateral acceleration, yaw rate, and vehicle slip angle; (b) front and rear lateral forces and tire sideslip angles.

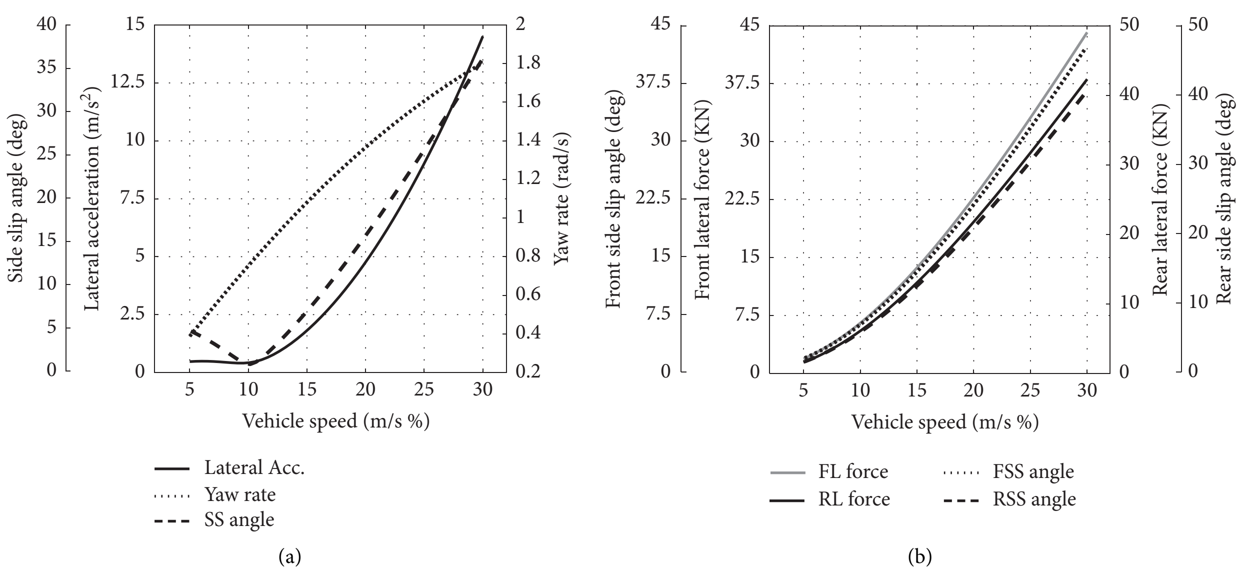


Figure 11: Conflict analysis of the lateral dynamics as a function of vehicle speed: (a) lateral acceleration, yaw rate, and vehicle slip angle; (b) front and rear lateral forces, and tire sideslip angles.

cornering stiffness improves the lateral acceleration while the decrease of the rear cornering coefficient has a negative impact on the lateral acceleration. In contrast, the increase in the vehicle speed has more effect on the lateral acceleration response than that of the lower speed, which is quite similar to the effect of the center of gravity position shifting. In the case of the front cornering coefficient, the wheelbase and the payload have approximately the same sensitivity versus the lateral acceleration.

Looking at Figure 13(b), it is obvious that the changes in the rear cornering stiffness coefficient and the center of gravity's longitudinal location have a considerable effect on the yaw rate sensitivity compared with other parameters. Marked deterioration of vehicular stability was found when the lowest value of the rear cornering coefficient was achieved. Similarly, vehicular stability became worse when the center of gravity is closer to the rear axle rather than the front axle. On the other hand, the vehicle speed, the front cornering stiffness, and the wheelbase have a considerable effect on the yaw rate and are predominantly symmetrical, unlike the payload effect, which is not noticeable.

The vehicle sideslip angle sensitivity due to the vehicle parameters' change is then illustrated in Figure 13(c). It is observed that the sideslip angle trend oscillates in a wide range with the increase/decrease of vehicle parameters. The main observation here is that the rear cornering stiffness coefficient has the most significant influence on the sideslip angle followed by the longitudinal CG location. The most interesting aspect of

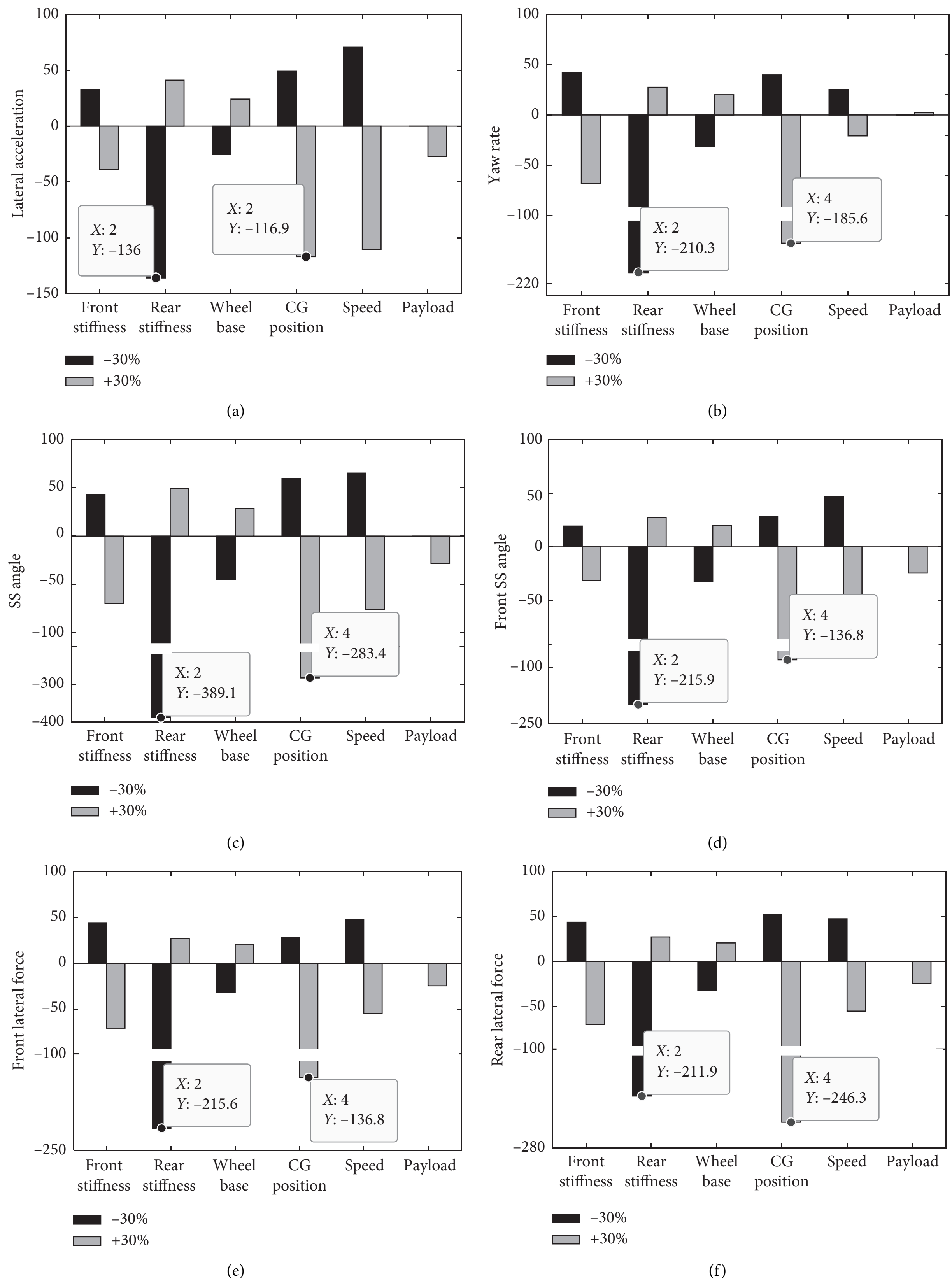


Figure 12: Influence of the vehicle's parametrical variation on the car lateral stability compared with the nominal situation.

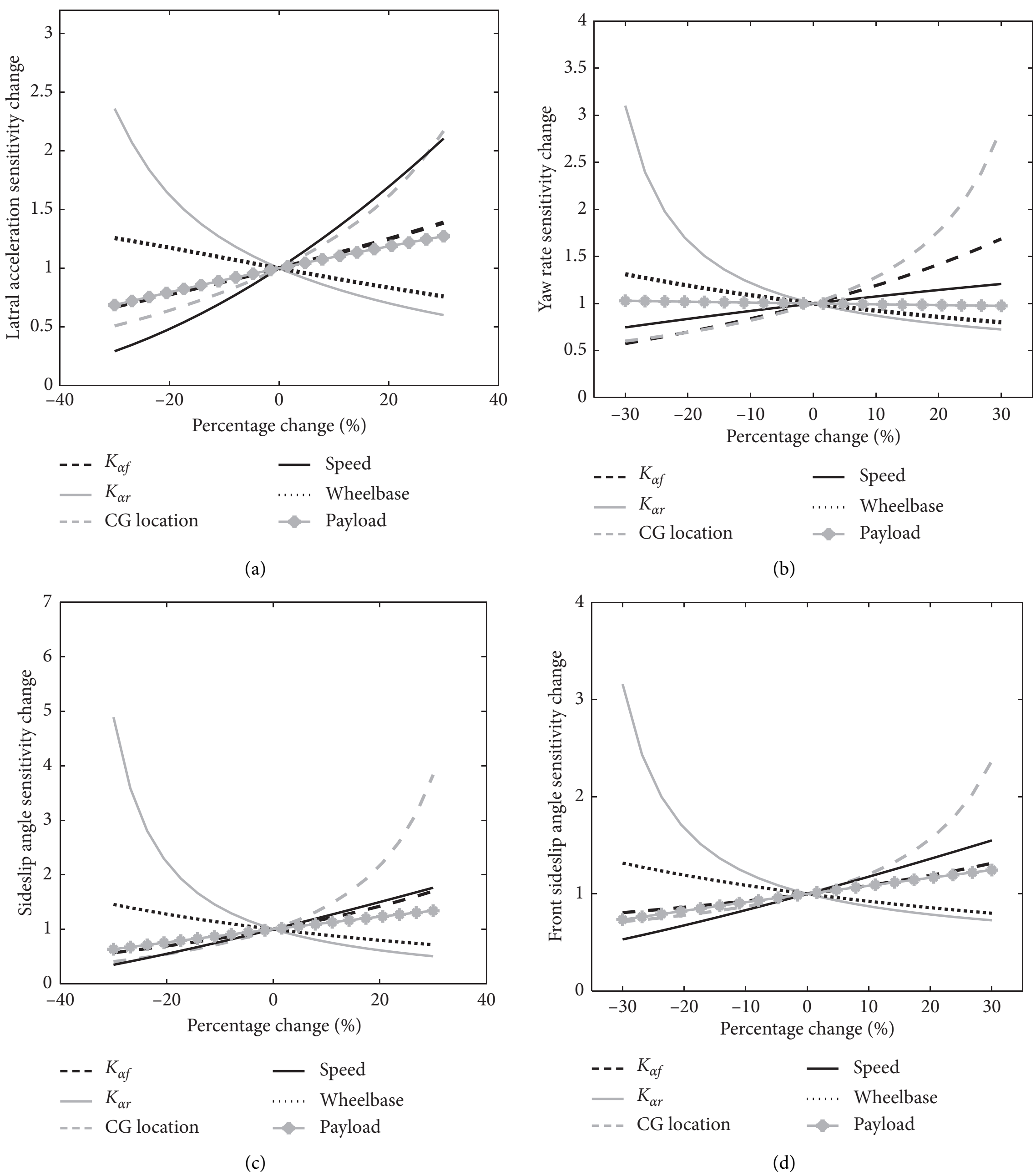
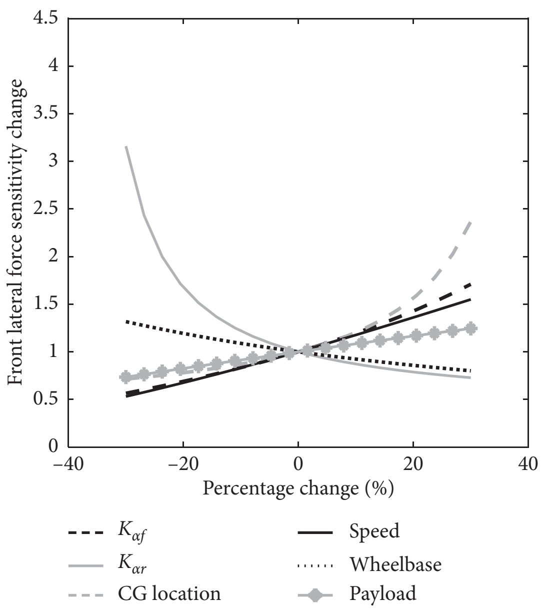
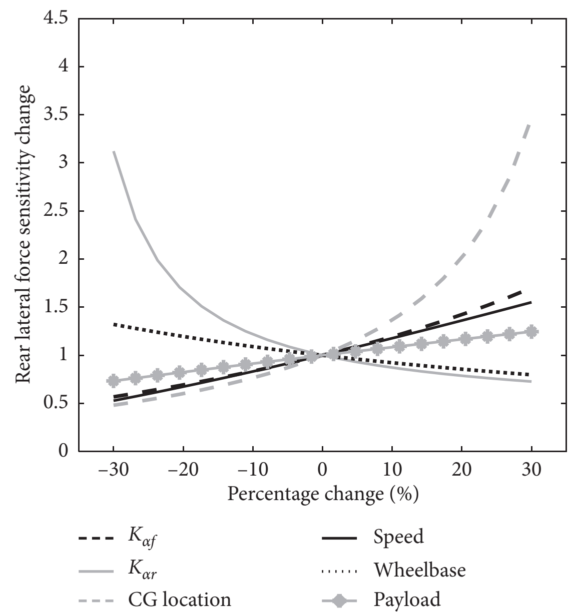


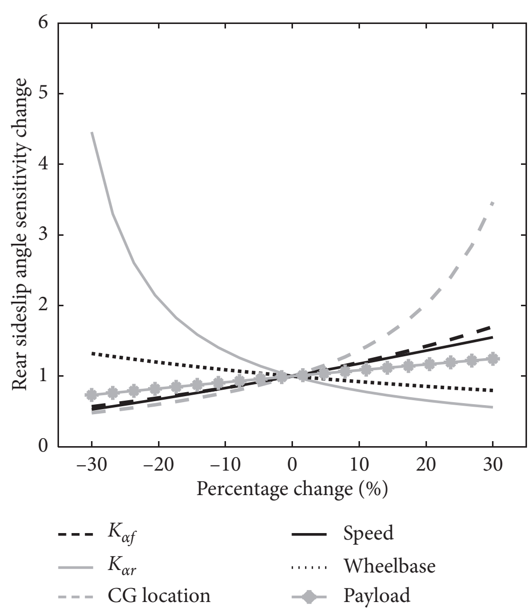
Figure 13: Continued.



(e)



(f)



(g)

Figure 13: Vehicular stability sensitivity against vehicle parameters variation (±30% nominal): (a) lateral acceleration, (b) yaw rate, (c) vehicle sideslip angle, (d) front sideslip angle, (e) front lateral force, (f) rear lateral force, and (g) rear sideslip angle.

this graph is that the sideslip angle is remarkedly sensitive to the small change in the rear tire stiffness and the load distribution percentage on the front and rear axles. Following the parametrical sensitivity analysis, the correlation sensitivity of both the front and the rear sideslip angles and the front and the rear lateral force versus the front and rear cornering stiffness, vehicle center gravity location, vehicle speed wheelbase, and payload are revealed in Figures 13(d), 13(e), 13(f), and 13(g). As expected, the aforementioned responses were most sensitive to the rear cornering stiffness and the CG longitudinal location, while in general, the other parameters presented lower correlation sensitivity on the vehicular response.

4.7. Steady-State Turning. It is essential to study the effect of vehicle parameters on the turning response properties, which describe how the vehicle's steering angle must be modified with a turning radius. The steering angle's direction and magnitude desired to keep the vehicle stable mostly depend on the load ratio on each axle and the tire's cornering stiffness. Therefore, the curvature response's sensitivity change is investigated versus the vehicle parameters such as tire cornering stiffness, wheelbase length, and the longitudinal position of the vehicle center of gravity.

Figures 14(a) and 14(b) display the correlation between the curvature response and vehicle parameters'

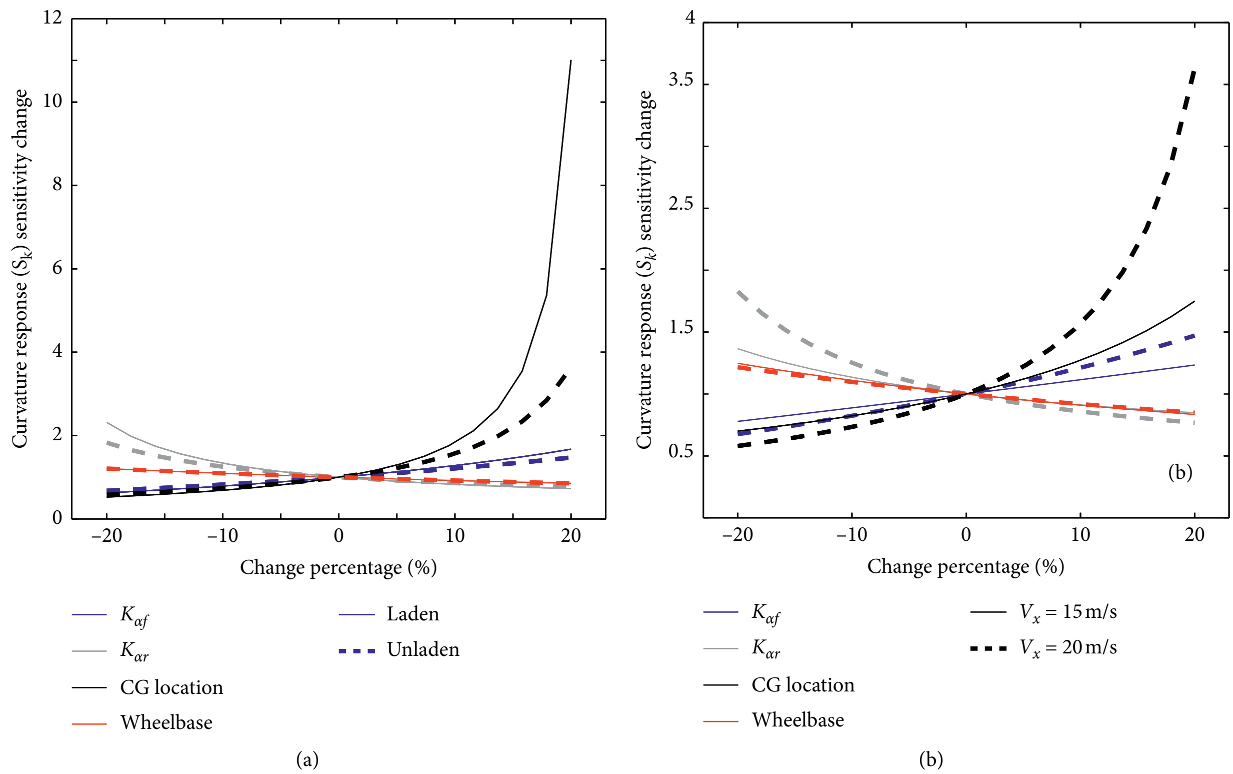


FIGURE 14: Curvature response sensitivity versus vehicle parameters variation (±20% nominal) for (a) laden and unladen conditions and (b) different driving speeds.

variation (±20% variation of their nominal values) using the fishhook maneuver in cases of both under laden and unladen conditions and two sets of the vehicle speed (15 and 20 m/s). Among all, the important observation here is that there is a significant impact of the vehicle parameters on the curvature response, particularly the change of the CG location at the laden condition. This is due to the increase in the rear wheel's load when the CG is shifted closer to the rear axle, and thereby the rear tire reaches the grip limit before the front tire, making the vehicle becomes critically oversteered. Thus, the highest curvature response is achieved, and the car might become unstable. On the contrary, the front tire reaches the grip limit before the rear tire when the CG is shifted closer to the front axle. In this situation, the vehicle tends to have another path with a larger radius to keep its dynamical stability, which corresponds to the minimum curvature response, and this phenomenon is called the understeer. This investigation indicated another important correlation between the curvature response and the tire cornering stiffness in which the tire cornering stiffness indicates the proportionality between the yaw moment and the vehicle sideslip angle, and hence indicates the vehicular directional stability. When the rear tire produces a greater moment than the front tire, the vehicle becomes stable, which reduces the sideslip angle effect. As indicated in Figures 14(a) and 14(b), the increase in the rear tire stiffness causes a decrease in the curvature response, which enhances the vehicular lateral stability, which contrasts with the front cornering tire stiffness. On the other dimension, the decrease in the rear tire stiffness and the increase of the front tire stiffness introduces an increase in the curvature response, which negatively contributes to vehicular stability.

Another important observation is that the vehicle mass significantly influences the curvature response sensitivity, as presented in Figure 14(a). In Figure 14(a), at fixed driving speeds and +20% shift in the CG to the rear axle, the curvature response presented a higher sensitivity change concerning the laden vehicle than that of the unladen vehicle. Furthermore, the lower rear tire stiffnesses gave the minimum curvature response at the unladen condition. As the rear tire stiffness increases, the curvature response correlation is conversely changed to present its lower values at the laden condition. On the other hand, as shown in Figure 14(b), for the same loading condition, the curvature response presented a higher sensitivity change versus most of the vehicle parameters when the driving speed is increased from 15 to 20 m/s. The results showed that the curvature response has remarkable reactivity with varying vehicle parameters to the vehicle speed variation. Finally, the curvature response responded weakly to the change in the wheelbase length for both the laden and unladen conditions. It can be concluded that the minimum curvature response is obtained at the higher rear tire stiffness, lower front tire stiffness, longer wheelbase length, and when the CG is closer to the front axle. Moreover, it is observed that the variation of the load and the vehicle speed plays an important role in vehicular stability, which can be strongly observed with the change of the vehicle parameters. These results agree with those obtained by earlier studies [41–43], which demonstrate the effectiveness of the linear model analyzing vehicles' dynamic behavior and evaluating their lateral criterion.

5. Conclusions

This paper comprehensively presented conflict and parametrical sensitivity analyses of the vehicular stability criteria versus the vehicle parameters' variation. In this manner, the linear bicycle model is derived and modeled using the Matlab/Simulink to describe the correlation between the vehicle parameter variation and the lateral vehicle stability. The simulations were accomplished considering the Fishhook 1a steering maneuver at a constant speed of 20 m/s. The selected parameters included the tire cornering stiffness coefficients, vehicle driving speed, CG longitudinal position, wheelbase length, and the payload.

Given the results of the sensitivity correlation analysis, the lateral vehicular stability correlated strongly to both the tire cornering stiffness and the CG longitudinal location. The reason is that the lateral tire force depends on the tire sideslip angle and the cornering stiffness, and subsequently has a direct influence on the vehicular stability. In the case of CG longitudinal location, the CG position is a key factor for reaching the grip limit of the front and the rear tires, and therefore has a significant effect on the lateral stability. Another essential observation is that the rate distribution is not the only property of the cornering stiffness coefficient, which impacts the lateral criterion, but the sum of both the front and the rear is also very important. According to the given results, more vehicular stability is achieved when the center of gravity is closer to the front axle rather than the rear axle. Furthermore, vehicles with a longer wheelbase ensure better lateral stability. It is also concluded that the vehicle's driving speed also has a noticeable effect and correlation sensitivity on the lateral stability, particularly in the case of lateral acceleration.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest concerning the research, authorship, and/or publication of this article.

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