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STUDY OF THE INFLUENCE OF LATERAL FORCES AND VELOCITY ON THE LATERAL DYNAMICS OF AUTOMOBILE

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Abstract

Stability of a car's trajectory of motion is the ability of a car to retain its required state of motion, under different conditions of motion. Depending on different states of motion, cars can lose direction of motion instability when there is a lateral force, due to vehicle speed, due to turning or braking the road with different grip coefficients on the sides of the wheel. In such complex moving conditions, cars need to keep a stable trajectory of movement under the driver's control. The paper examines the stability of the car's trajectory in linear motion conditions with the influence of lateral forces and the velocity of the vehicle, these two factors act to change the state of movement of the vehicle, which significantly affects the safety of the vehicle's movement. The authors looked at the effect of vehicle velocity and lateral forces on vehicle transverse dynamics: lateral forces caused by horizontal winds, inclination of the road surface, speed of movement of the vehicle acting on the entire body create centrifugal inertial forces; this force acts to cause the tires to deform. At this point the vehicle is shifted from its original trajectory. In the research content, the authors built a lateral Dynamics Model, in which the influencing factors are set as inputs to the model including vehicle velocity and transverse wind forces, output is the rotation angle of the body, transverse acceleration and horizontal displacement of the vehicle. The simulation results showed that the effect of vehicle speed was relatively large: lateral displacement increased by 228 % at a speed of 120 km/h. Therefore, when driving on the highway, there should always be driver control to ensure that the car does not deviate from the lane.

Keywords: Automotive dynamics, steering dynamics, trajectory of motion, MATLAB/Simulink, lateral dynamics of automotive.

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1. Introduction

Depending on different states of motion, cars can lose direction of motion instability when there is a lateral force (due to the action of wind or inclined road surface), due to vehicle speed, due to turning or braking the road with different grip coefficients on the sides of the wheel. In such complex moving conditions, the car must keep a stable trajectory of movement under the driver's control. There are many studies related to automobile motion stabilization such as: Research on optimizing control inputs to stabilize the horizontal trajectory of the vehicle [1], in these studies refer to transverse automobile dynamics with the effect of tire friction against the road surface, stabilization of the car's horizontal trajectory by controlling the operation of the differential [2], algorithm studies for estimating the transverse velocity and transverse force of tires affecting vehicle stability when cornering, Simulation results show that the developed system can reliably estimate the upper and lower bounds of vehicle lateral variables during both steady and transient maneuvers [3], building the horizontal stabilization algorithm of cars [4], development of single-track transverse dynamics models for automobiles [5], study of driver models applied to automotive dynamics, a brief look beyond is added to better complete the view on the involved task of driving and driver modeling for automobile dynamics application [6], the paper studies the horizontal stability control of the car using front-wheel steering and in combination with the brake system [7]. When studying the stability of the automobile fully, it is necessary to consider the dynamics of the car [8], stability analysis illustrating the influence of the following attributes on the stability and performance of lateral vehicle control: Vehicle handling properties, virtual force application point, sensing location, controller damping [9]. The paper deals with theoretical research on the influence of two factors when cars are on the road, transverse force and vehicle velocity, on horizontal stability. Consider the degree of influence of these two factors on the horizontal displacement of the body relative to the direction of linear motion. The relationship between driver and lateral dynamics automotive is shown as **Fig. 1**.

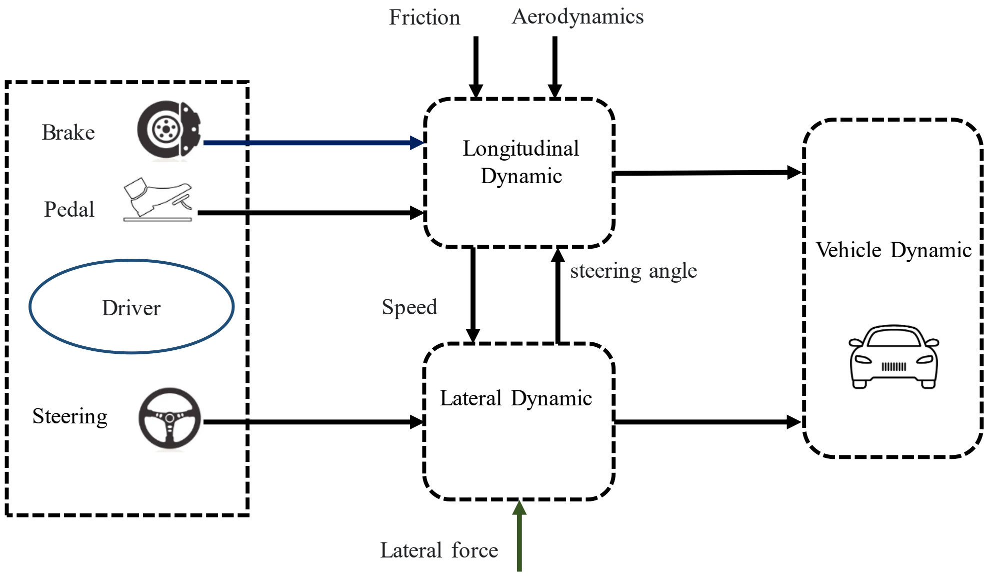

Fig. 1. Driver relations and automotive dynamics

Stability of the trajectory of the car's movement through the car's on-board systems: trajectory stabilization through braking [10], steering [11], traction [12]. These systems affect the longitudinal dynamics, the transverse dynamics of the car, in addition to the effect of velocity, friction in the system, tire aerodynamics, lateral forces (transverse wind forces) acting on the car when moving. This study focuses on the effect of velocity on transverse dynamics with different lateral forces when cars are moving in a straight line.

2. Materials and methods

2. 1. Dynamics modeling

Automotive dynamics is the basic theory that played an important role in the development of the automotive industry. [13] consider the pattern of movement of the automobile in the horizontal plane with elastic wheels represented as **Fig. 2** [5, 14].

Use Newton's 2nd law for the equation of motion of front wheel cars. There is a system of differential equations moving along the longitudinal direction x, the horizontal direction y and the body rotation angle θ_v.

$$\ddot{x} = \dot{y}\dot{\theta}_V + \frac{1}{m_v}\left[\left(F_{xfl} + F_{xfr}\right)\cos\theta_{FW} - \left(F_{yfl} + F_{yfr}\right)\sin\theta_{FW} + F_{xrl} + F_{xrr}\right], \quad (1)$$

$$\ddot{y} = -\dot{x}\dot{\theta}_V + \frac{1}{m_v}\left[\left(F_{xfl} + F_{xfr}\right)\sin\theta_{FW} + \left(F_{yfl} + F_{yfr}\right)\cos\theta_{FW} + F_{yrl} + F_{yrr}\right] + F_w, \quad (2)$$

$$\ddot{\theta}_V = \frac{1}{I_z}\begin{bmatrix} L_f\left(F_{xfl} + F_{xfr}\right)\sin\theta_{FW} + L_f\left(F_{yfl} + F_{yfr}\right)\cos\theta_{FW} - L_f\left(F_{yrl} + F_{yrr}\right) - \\ -\frac{T_f}{2}\left(F_{xfl} - F_{xfr}\right)\cos\theta_{FW} + \frac{T_f}{2}\left(F_{yfl} - F_{yfr}\right)\sin\theta_{FW} - \\ -\frac{T_r}{2}\left(F_{xrl} - F_{xrr}\right) + F_w \cdot L_w \end{bmatrix}. \quad (3)$$

Here, m_v, I_z: mass and Mass moment of inertia of the car; θ_{FW}: front wheel angle; F_{xfr}, F_{yfr}, F_{xrr}, F_{yrr}: force is applied vertically and horizontally to the right front and right rear wheels; F_{xfl}, F_{yfl}, F_{xrl}, F_{yrl}: force is applied vertically and horizontally to the left front and left rear wheels; F_w: lateral forces; L_f, L_r, L_w: distance from the center of gravity of the car to the front and rear wheel axles, lateral force setpoint is concentrated to the center car; θ_v: body rotation angle; y, x: shifting the body horizontally and vertically.

With the assumption of constant longitudinal velocity, the equation of differential motion of a car is reduced as follows:

$$\ddot{y} = -\frac{1}{m_v v_x}\left(C_f + C_r\right)\dot{y} - \frac{1}{m_v v_x}\left(L_f C_f + L_r C_r\right)\dot{\theta}_V - v_x\dot{\theta}_V + \frac{C_f}{m_v}\theta_{FW-R}, \tag{4}$$

$$\ddot{\theta}_V = -\frac{1}{I_z v_x}\left(L_f{}^2 C_f + L_r{}^2 C_r\right)\dot{\theta}_V - \frac{1}{I_z v_x}\left(L_f C_f - L_r C_r\right)\dot{y} + \frac{L_f C_f}{m_v}\theta_{FW-R}. \tag{5}$$

In which the lateral force acting on the tire is used the formula below:

$$F_{yf} = C_f \alpha_f = C_f\left(\theta_{FW-R} - \frac{\dot{y} + L_f\dot{\theta}_V}{v_x}\right), \tag{6}$$

$$F_{yr} = C_r \alpha_r = C_r\left(\theta_{FW-R} - \frac{\dot{y} - L_r\dot{\theta}_V}{v_x}\right). \tag{7}$$

With V_x: longitudinal velocity of the car; C_f, C_r: front and rear tire stiffness. α_f, α_r: sliding angles of the front wheel and rear wheel.

(4) and (5) are used to simulate the effect of lateral forces (lateral wind forces) and velocities on automobile lateral dynamics.

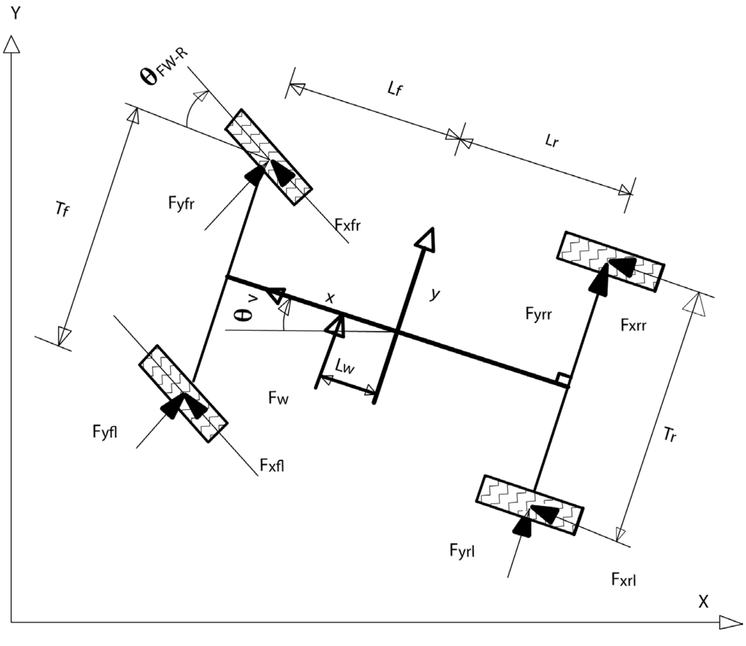

Fig. 2. Lateral dynamics model of a car with lateral force F_w

2. 2. Simulation model

The model block diagram is constructed with model inputs of automobile velocity, focusing lateral forces, steering angle, and model outputs of transverse acceleration, lateral displacement, and body rotation angle [15], represented as **Fig. 3**.

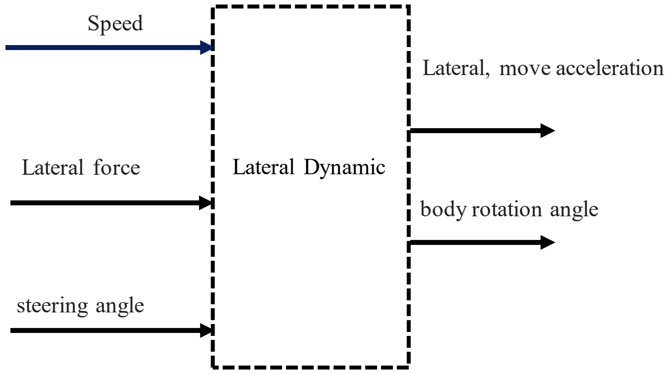

Fig. 3. Block diagram representing horizontally dynamics of automotive

Using Matlab/Simulink software (Matlab R2023b (23.2.0.2365128)) to simulate the effect of lateral forces and velocity on automobile dynamics, the simulation model is shown as **Fig. 4** and submodels from **Fig. 5–8** [8].

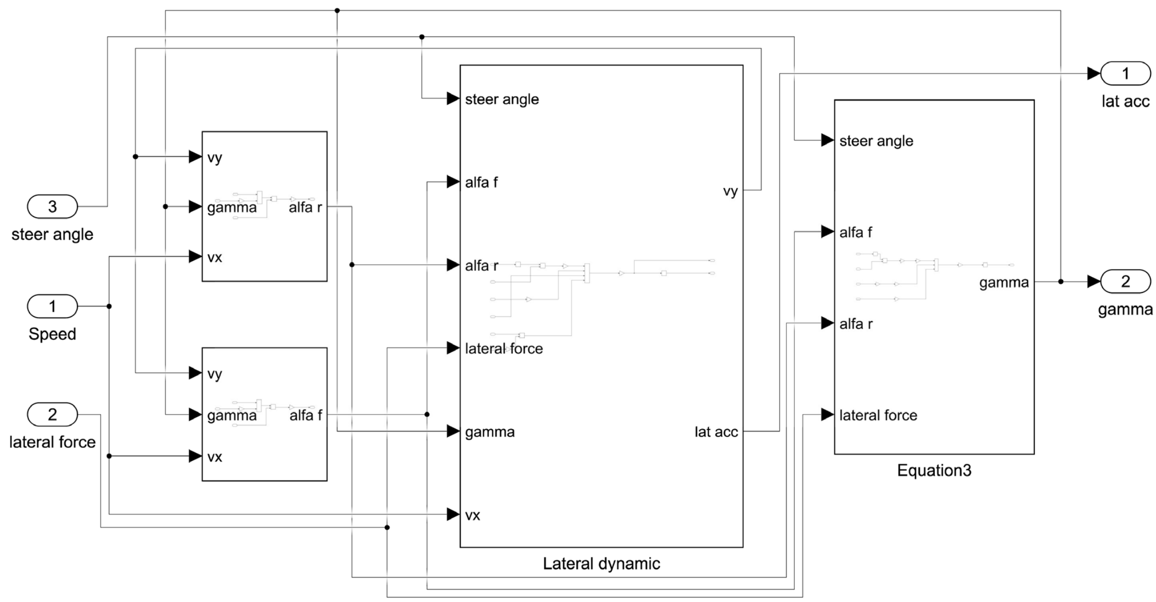

Fig. 4. Matlab/Simulink model simulating horizontal dynamics of automobile

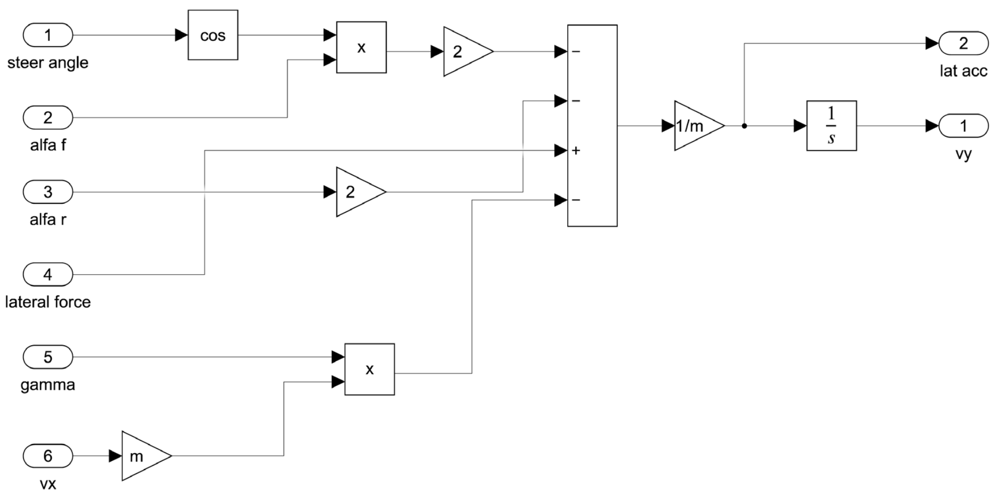

Fig. 5. Simulink model showing lateral velocity and acceleration

Where: the submodel represents the velocity and acceleration of the vehicle body horizontally (**Fig. 5**); the submodel represents the angle of rotation of the body (**Fig. 6)**; The Simulink model represents the sliding angle of the rear wheel (**Fig. 7**); The Simulink model represents the sliding angle of the front wheel (**Fig. 8**).

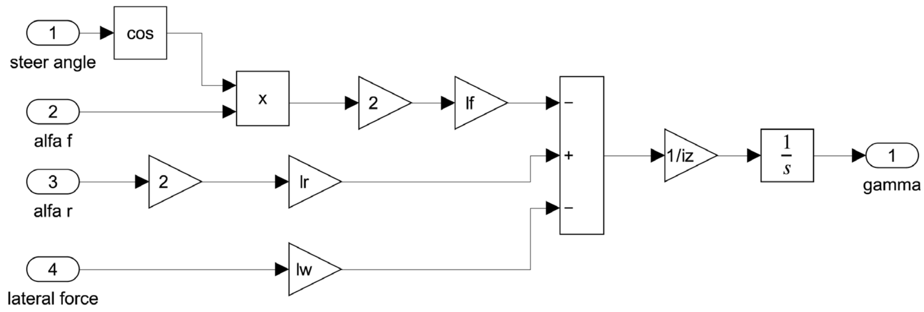

Fig. 6. Simulink model showing body rotation angle

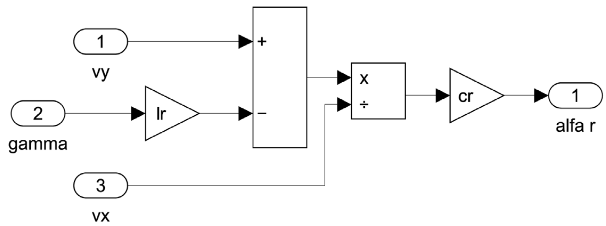

Fig. 7. Simulink model showing sliding angle of the rear wheel

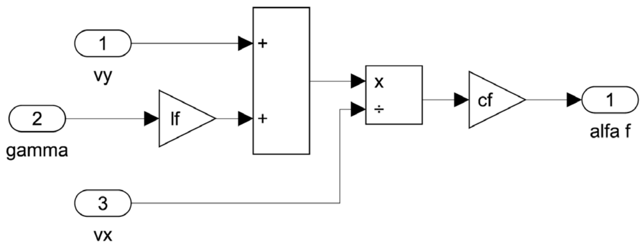

Fig. 8. Simulink model showing sliding angle of the front wheel

The simulation parameters are as shown in the **Table 1** [14].

Table 1
Parameters for simulating lateral dynamics automobile

Parameter	Symbol	Unit	Value
Mass moment of inertia of the car	I_z	kgm^2	2500
Mass of car	m_v	kg	1470
Front tire stiffness	C_f	N/rad	100.000
Rear tire stiffness	C_r	N/rad	110.000
distance from the lateral force to the center	L_w	m	0.4
Distance from center to front wheels	L_f	m	1.3
Distance from center to rear wheels	L_r	m	1.3
Speed car	V_x	m/s	Online measured

3. Results and discussion

Simulate the influence of automobile velocity, lateral forces on automobile transverse dynamics with the assumptions: the lateral force (F_w) is calculated according to the document [16] (with wind level 8, 9, 10) corresponding to the values F_w: 3000 N, 5000 N, 7000 N; the speed of surveyed cars at the maximum speeds prescribed for city roads, intercity roads and expressways, respectively: 60 km/h, 80 km/h, 120 km/h; survey in the case of a linear motion car.

Effect of velocity on body rotation angle, lateral acceleration, lateral move. The simulation is carried out at speeds of 60 km/h, 80 km/h, 120 km/h; the output values as **Table 2** and represented by **Fig. 9–11**.

Table 2
Maximum value results of transverse dynamics parameters when changing automobile velocity

Speed car (km/h)	60	80	120
Body rotation angle (rad)	0.028	0.036	0.048
Lateral acceleration (m/s^2)	0.8	1.3	1.9
Lateral move (m)	0.25	0.41	0.82

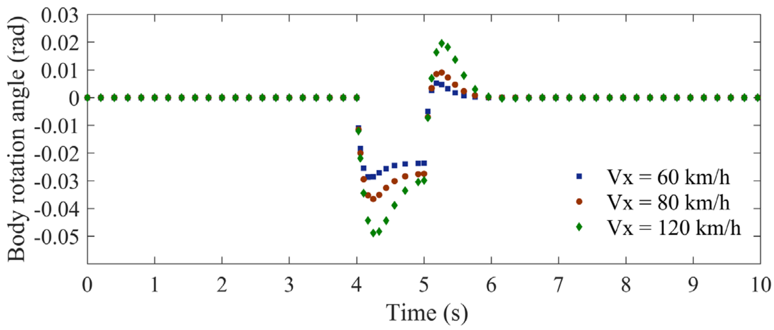

Fig. 9. Simulation body rotation angle

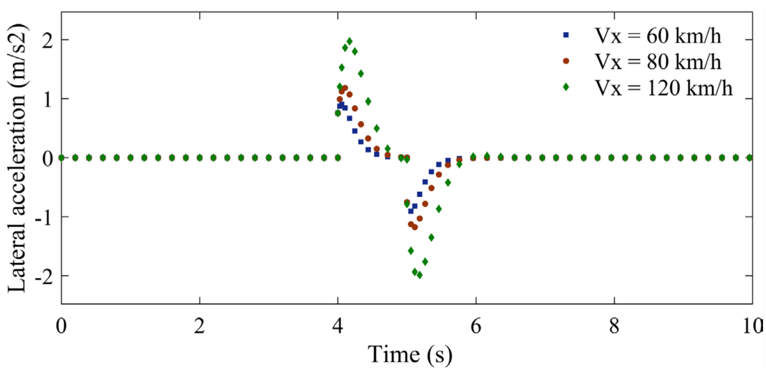

Fig. 10. Simulation lateral acceleration

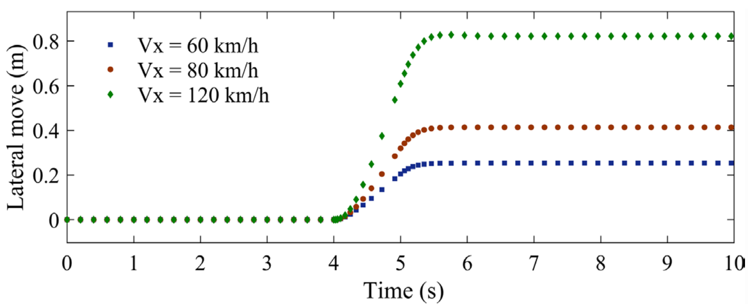

Fig. 11. Simulation lateral move

When increasing the speed along the car from 60 km/h to 80 km/h, the body rotation angle increased by 28.6 %; horizontal acceleration increased by 62.5 %; lateral displacement increased by 64 %; continuing to increase the speed to 120 km/h, the body rotation angle increased by 71.4 %; transverse acceleration increased by 137.5 %; Lateral displacement increased by 228 % (**Table 2**). Therefore, when driving on the highway (V = 120 km/h) there must always be driver control to ensure that the car does not slip out of the lane [17].

The effect of transverse forces on the parameters of body rotation θ.-V., horizontal acceleration a_v, horizontal displacement x_v. Simulated at the transverse forces F_w = 3000 N, 5000 N, 7000 N are the output values as shown in **Table 3** and represented by **Fig. 12–14**.

Table 3
Biggest results of lateral dynamics parameters when lateral force changes F_w

Lateral force F_w (N)	**3000**	**5000**	**7000**
Body rotation angle (rad)	0.029	0.048	0.067
Lateral acceleration (m/s^2)	0.8	1.5	2.1
Lateral move (m)	0.26	0.42	0.59

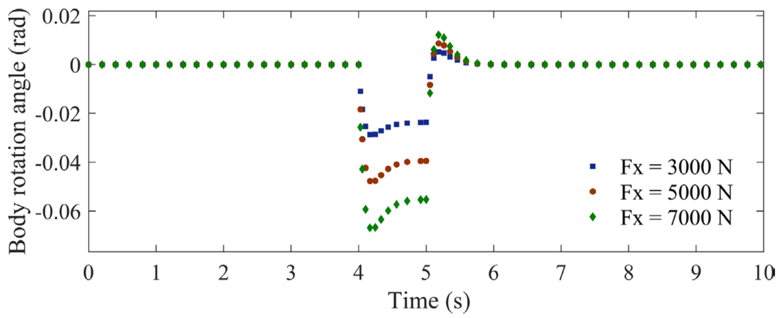

Fig. 12. Simulation body rotation angle

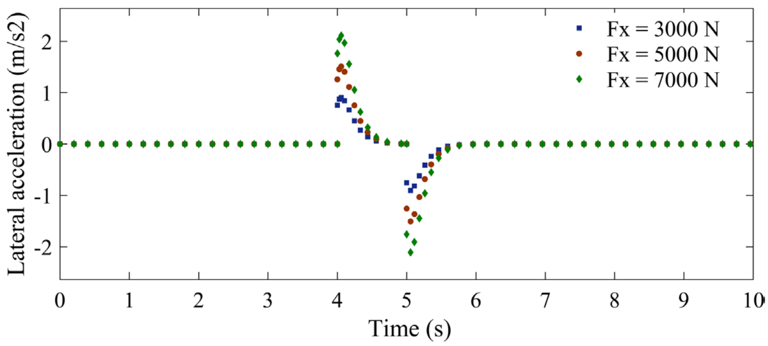

Fig. 13. Simulation lateral acceleration

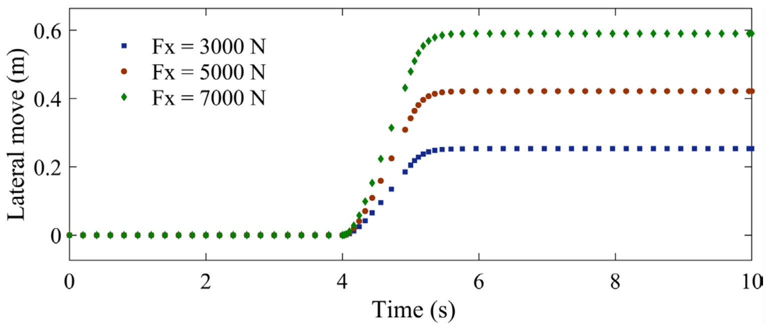

Fig. 14. Simulation lateral move

When increasing the horizontal force F_w from 3000 N to 5000 N, the hull rotation angle increased by 65.5 %; transverse acceleration increased by 87.5 %; lateral displacement increased by 61.5 %; continuing to increase the horizontal force to 7000 N, the body rotation angle increased by 131 %; horizontal acceleration increased by 162.5 %; lateral displacement increased by 126.9 % (**Table 3**). It is possible to see that when increasing horizontal power (with V = 60 km/h) the car can still ensure stability.

The study was only conducted on simulations with a few reference transverse speed and force values that did not fully reflect the actual conditions when driving on the road (such as sharp steering). Therefore, more studies are needed for this case, and further research is needed on a controller to automatically fix the problem of horizontal displacement of the body when the driver does not act on the steering system in time.

4. Conclusions

In conditions where road testing is very difficult to perform (due to cost, time, safety), building models and simulating factors affecting the stability of cars is necessary to allow simulation in a variety of conditions. The paper built a model of automotive transverse dynamics and investigated the influence of velocity and lateral forces on automotive dynamics. The simulation results show that transverse forces and velocity greatly affect the horizontal stability of the car (change of direction of movement, slippage and lane deviation), in which, the speed factor greatly affects the lateral displacement of the vehicle, which can lead to the vehicle losing direction of movement and shifting from the running lane by 228 % at a speed of 120 km/h. Therefore, it is necessary to have appropriate controls of the driver in road conditions, horizontal winds, turning the car, especially, it is necessary to reduce the vehicle speed to the minimum regulation when there is a horizontal force (horizontal wind force).

Conflict of interest

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

Financing

The study was performed without financial support.

Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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