Simulation of Influence of Crosswind Gusts on a Four Wheeler using Matlab Simulink

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Abstract-When driving a vehicle on the road, the driver has to compensate continuously for small directional deviations from the desired course due to disturbances from the crosswinds. These types of deviations have a tiring effect on the driver and should therefore be minimized. When the magnitude of these disturbances increases, the directional deviation might become so large that the driver will have difficulties in compensating for it and will thereby affect the traffic safety. The objective of this research work is to increase the understanding of the crosswind sensitivity of passenger cars and to find solutions to increase the crosswind stability. This work focuses at the basic motion characteristics of the vehicle travelling in a straight line, when it is acted on by a lateral wind disturbance. Using detailed vehicle simulation models and evaluation of crosswind performance using Matlab Simulink software, the stability characteristics of the vehicle are experimented by varying different parameters like the velocity of the vehicle, velocity of wind, position of attack and angle of attack. By analyzing the different simulation results, the influential parameters are identified and it is inferred that a moment in the direction opposite to that of a crosswind must be applied when a crosswind is detected. In order to achieve this, a system is developed which varies the torque at the individual wheels thereby creating a moment in the vehicle which opposes the crosswind moment. The moment caused by the variation in individual wheel torque will counteract the crosswind and help the vehicle to maintain its stability. The model of this system is created in Matlab Simulink, simulated and compared.

Keywords*-crosswind stability; simulation; vehicle dynamics;*

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Introduction

Vehicles travelling at high speeds encounter lateral wind disturbances from strong crosswind gusts, which have a great influence on the stability of the vehicle leading to accidents and also cause discomfort for the driver. A majority of rollover and loss of control crashes are due to poor appreciation of the general dynamics and stability issues of the vehicle. Vehicle Dynamics refers to the motion of a motor vehicle and the various forces that act upon the vehicle when in motion. In early studies of road vehicle aerodynamics, the focus was mainly on the reduction of drag in order to increase the maximum speed and lower the fuel consumption. As the performance increased, the need to reduce lift increased, and the expansion of highways with increased exposure to crosswinds led to a need to improve crosswind aerodynamics. Simulations provide a powerful tool when analysing the effect of several parameters on the vehicle performance mainly due to the repeatability of the manoeuvres used for the evaluation. This is especially valuable when studying crosswind performance, since the ambient conditions are very hard to monitor and control when performing field experiments. In addition, simulations provide the possibility of evaluating manoeuvres that are potentially dangerous to perform without jeopardizing the safety of the driver and his fellow road users.

I. VEHICLE DYNAMICS MODEL

A. Passenger Car Dynamics

Passenger Car Dynamics is a branch of classical mechanics, which deals with the motion of the vehicle generated by the steering action and other forces acting on the vehicle body. A vehicle moving without obstruction in a horizontal plane, can be disturbed laterally by some external force acting on the vehicle in the lateral direction. Understanding dynamics of a vehicle will help improve the directional stability of the vehicle. Directional stability is the tendency of the moving body to keep the body in its original motion. If a vehicle is directionally stable, a restoring moment is produced in a direction opposite to the disturbance and this makes the vehicle return to its original direction.

B. Passenger Car Model

A vehicle mathematical model of a passenger car is assumed and by applying a four-wheeled vehicle model, it is possible to obtain fundamental knowledge of the dynamics of passenger cars. The wheels are regarded as weightless and the rigid body represents the total vehicle weight in the vehicle mathematical model, as shown in Fig. 1.

The coordinate system is fixed to the vehicle with its origin at the center of gravity, the x-axis in the longitudinal direction, the y-axis in the lateral direction and the z-axis in the vertical direction.

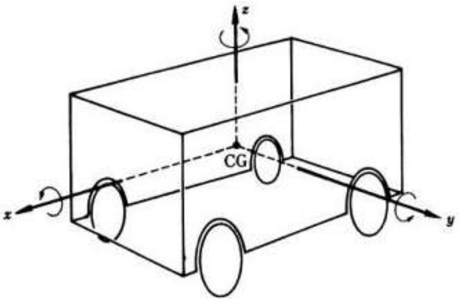

Fig. 1. Vehicle Dynamics Model.

The vehicle motion with this coordinate system has six independent degrees of freedom. They are,

1. Vertical motion in z direction
2. Left and Right motion in y direction
3. Longitudinal motion in x direction
4. Rolling motion in x-axis
5. Pitching motion in y-axis
6. Yawing motion in z-axis

These can be grouped into two main groups. The first group consists of motion 1, 3 and 5 as these motions are generated without any direct relation to the steering. The second group consists of motion 2, 4 and 6 as these motions are generated by steering the vehicle.

II. GOVERNING EQUATIONS OF MOTION

The vehicle motion with fixed coordinates to the ground is used to express the equations of motion of the vehicle along a straight road, since the calculations are easier and more convenient.

The X-Y coordinates are fixed on the ground with the straight road direction on the X-axis and the perpendicular Y-axis. The yaw angle which is the angle between the vehicle longitudinal axis and the X-axis is θ. The direction of lateral forces, Y_f, Y_r acting on the front and rear tires is taken to be coinciding with the Y-direction and the vehicle motion can be expressed.

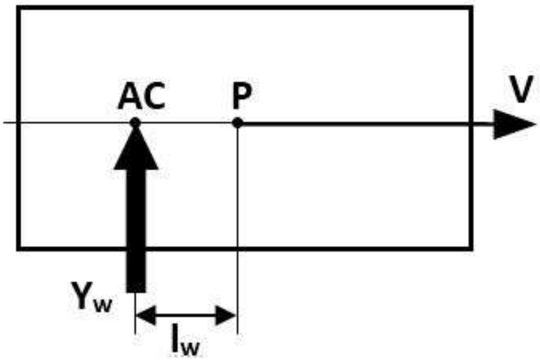

Fig. 1. Lateral Force by Side Wind.

The motion of center of gravity in the Y-direction and the yaw moment is given by the Equation 1 and Equation 2.

$$m\frac{d^2y}{dt^2} = 2Y_f + 2Y_r \tag{1}$$

$$I\frac{d^2\theta}{dt^2} = 2l_fY_f + 2l_rY_r \tag{2}$$

The angle formed by the wheels heading direction and the X-axis at the front θ_f is $\theta + \delta$ and the angle at the rear θ_r is θ. The angle formed by the wheels traveling direction is γ_f and γ_r in the front and rear respectively. The front and rear tire side-slip angle is given in Equation 3 and Equation 4.

$$\beta_f = \gamma_f - \theta_f \tag{3}$$

$$\beta_r = \gamma_r - \theta_r \tag{4}$$

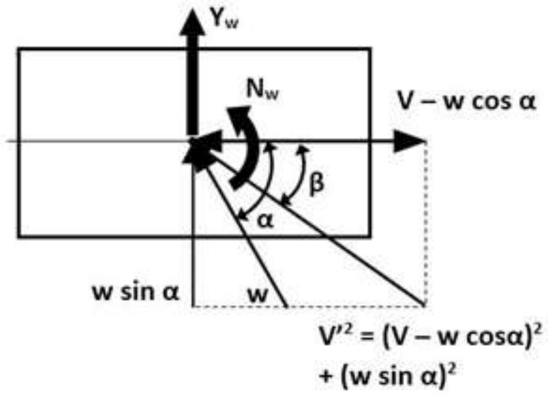

Fig. 2. Lateral Force and Yaw Moment caused by the crosswind.

The lateral forces acting on the front and rear wheels is Y_f and Y_r as shown in Equation 5 and Equation 6.

$$Y_f = -K_f\beta_f \tag{5}$$

$$Y_r = -K_r\beta_r \tag{6}$$

Substituting the values of Y_f, Y_r, β_f, β_r in Equation 1 and Equation 2, we get Equation 7 and Equation 8.

$$m\frac{d^2y}{dt^2} + \frac{2(K_f + K_r)}{V}\frac{dy}{dt} + \frac{2(l_fK_f - l_rK_r)}{V}\frac{d\theta}{dt} - 2(K_f + K_r)\theta = 2K_f\delta \tag{7}$$

$$\frac{2(l_fK_f - l_rK_r)}{V}\frac{dy}{dt} + I\frac{d^2\theta}{dt^2} + \frac{2(l_f^2K_f + l_r^2K_r)}{V}\frac{d\theta}{dt} - 2(l_fK_f + l_rK_r)\theta = 2l_fK_f\delta \tag{8}$$

Equation 7 and Equation 8 are the vehicle equations of motions with respect to the fixed coordinates of the ground. The equations describes the lateral displacement, y and the yaw angle, θ with the steer angle, δ as in [1].

If the vehicle is travelling in a straight road at a velocity, V, as shown in Fig. 2, is subjected to a lateral wind velocity, w at an angle α, the lateral force, Y_w, and yaw moment, N_w, acting are expressed as Equation 9 and Equation 10.

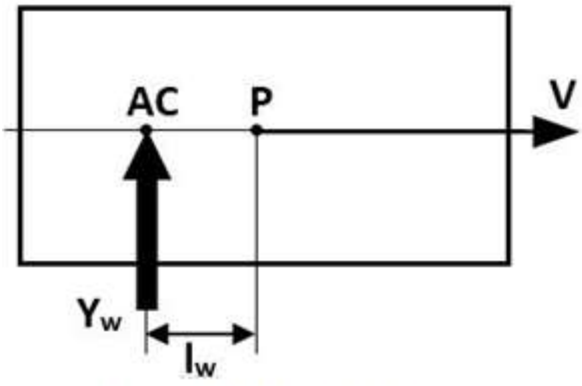

Fig. 3. Lateral Force by Side Wind.

TABLE I. PARAMETERS WITH THEIR VALUES THAT WAS USED FOR THE SIMULATION

Vehicle Parameters	**Value**	**Unit**
m	1700, 2025	kg
I	2500	kg-m^2
l_f	1.1	m
l_r	1.5	m
K_f	6,000,070,000	N/rad
K_r	65000, 75000	N/rad
V	40, 50, 60	m/s
w	25	m/s
l_w	0.6, 0.3, -0.3	m
ρ	1.29	kg/m^3
S	1.5	m^2
C_y	0.96	
α	90	degree

$$Y_w = C_y (\rho/2) S [(V-w \cos\alpha)^2+(w \sin\alpha)^2] \tag{9}$$

$$N_w = C_n (\rho/2) lS [(V-w \cos\alpha)^2+(w \sin\alpha)^2] \tag{10}$$

Where, C_y is the lateral force coefficient, C_n is the yawing moment coefficient, ρ is the air density, S is the vehicle frontal area and l is the vehicle dimension.

The acting point of the lateral force, Y_w, is called the Aerodynamic Center (AC) and the distance between AC and the center of gravity is l_w as shown in Fig. 3. The yaw moment acting on the vehicle N_w can be written as:

$$N_w = -l_w Y_w \tag{11}$$

C_y and C_n change with β, and β changes with vehicle motion. If this variable vehicle motion is not long, Y_w and N_w can be assumed independent of the vehicle motion, thus simplifying the analysis. Anticlockwise rotation is assumed to be positive.

$$m\frac{d^2y}{dt^2} + \frac{2(K_f + K_r)}{V}\frac{dy}{dt} + \frac{2(l_fK_f - l_rK_r)}{V}\frac{d\theta}{dt} - 2(K_f + K_r)\theta = Y_w \tag{12}$$

$$\frac{2(l_fK_f - l_rK_r)}{V}\frac{dy}{dt} + I\frac{d^2\theta}{dt^2} + \frac{2(l_f^2K_f + l_r^2K_r)}{V}\frac{d\theta}{dt} - 2(l_fK_f + l_rK_r)\theta = -l_wY_w \tag{13}$$

Since this is an open loop test with no steering corrections and the steering wheel fixed, the vehicle equations of motions when acted by a lateral force Y_w can be written as Equation 12 and Equation 13.

The parameters of the passenger car used for this simulation are shown in Table I.

III. THE SIMULATION WORK

Since the Simulink model of the whole vehicle is used, MATLAB is the most relevant software used for this purpose. MATLAB is the abbreviation of matrix laboratory. It is a multi-paradigm numerical computing environment and fourth generation programming language. Although MATLAB indented primarily for numerical computing, an optional toolbox allows access to symbolic computing capabilities. An additional package, Simulink, adds graphical simulation and Model Based Design for dynamic and embedded systems.

Consider the situation where the vehicle is subjected to a sudden lateral gust with the front steering angle fixed to zero. The equations of motion are rewritten to obtain $\frac{d^2y}{dt^2}$ and $\frac{d^2\theta}{dt^2}$. A MATLAB Simulink model was constructed to simulate the equations.

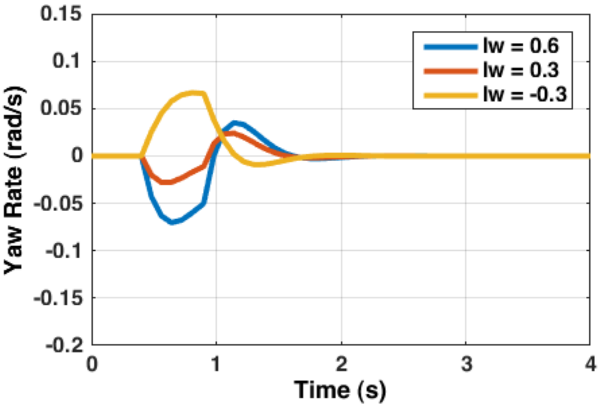

Fig. 4. Graph between Yaw Rate and Time at V = 40 m/s

IV. SIMULATION RESULTS

The parameters were uploaded and the MATLAB simulation was started. The simulation was completed and the various results were generated. By varying the different values of l_w i.e. the point of attack of the crosswind, three different plots were generated.

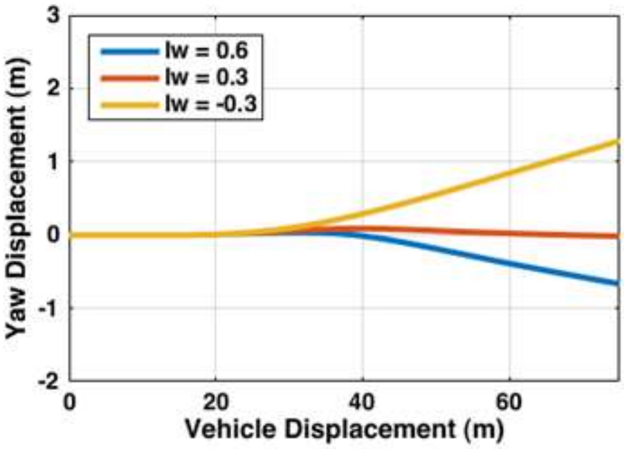

Fig. 5. Graph between Yaw Displacement and Vehicle Displacement at V = 40 m/s

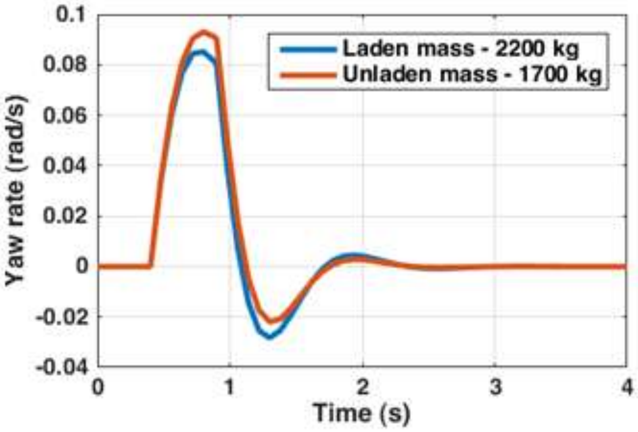

Fig. 6. Graph between Yaw Rate and Time for different Mass

All the three plots were multi-plotted and the graphs were obtained. The graphs generated are: Y (m) Vs X (m) and Yaw rate (rad/s) Vs Time (s).

The first graph shown in Fig. 4, depicts the relation between the yaw distance in metres and distance the vehicle has travelled in metres. Since the l_w lies before the CG of the vehicle, the vehicle yaws towards the left and for positive l_w values, it yaws to the right.

The second graph shown in Fig. 5, depicts the relation between the yaw rate in rad/s and the time in seconds. For the negative l_w value, the yaw rate is anticlockwise and for the positive l_w values, the yaw rate is clockwise in direction. The graphs in Fig. 4 and Fig. 5 were obtained by simulating at a vehicle velocity of 40 m/s. The simulation was further done by varying the vehicle velocity to 50 m/s and 60 m/s and similar graphs were obtained.

It was evident that the stability of the vehicle against crosswind gusts decreased as the velocity of the vehicle increased and as a result there was a greater yaw rate and yaw distance. It was also found by simulations that the yaw rate was directly influenced by mass of the vehicle, vehicle dimensions and cornering stiffness.

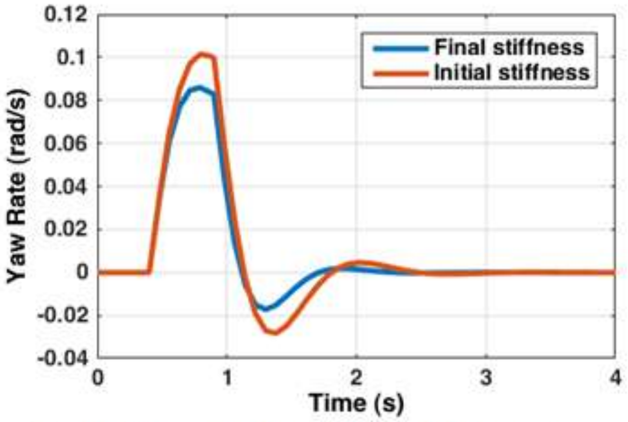

Fig. 7. Graph between Yaw Rate and Time for 15% increase in Cornering Stiffness

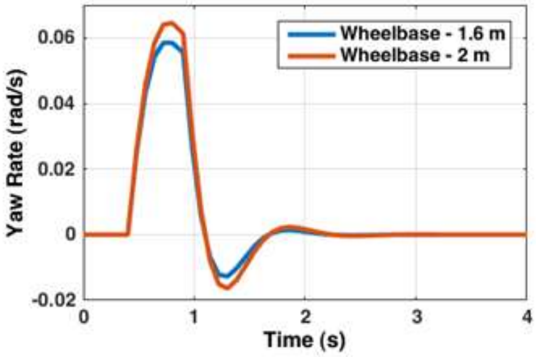

Fig. 8. Graph between Yaw Rate and Time for different Wheelbase

A comparison on the variation of yaw rate with laden and un-laden mass conditions was simulated and the graph is shown in Fig. 6. It was found that the car with greater mass was more resistant to crosswinds.

The cornering stiffness of the tires were varied and the simulations were performed. It was found that an increase in the cornering stiffness increased the crosswind stability. The Fig. 7 compares the yaw rate when there is a 15% increase in the cornering stiffness values and it is noticeable that there is a reduction in yaw rate with higher stiffness.

It was also found out by simulation that vehicles with longer wheelbase was more resistant to crosswinds. The Yaw rate graph for different wheelbase is shown in Fig. 8.

V. THE PROPOSED SYSTEM

Consider a four wheel drive vehicle travelling in a straight line as shown in Fig. 9. It is subjected to a lateral wind disturbance and a crosswind moment N_w acts on the vehicle. When there is no external disturbance, the moment caused by the right side wheels must be equal to the moment caused by the left side wheels, for the vehicle to travel in a straight line. This is shown in Equation 14.

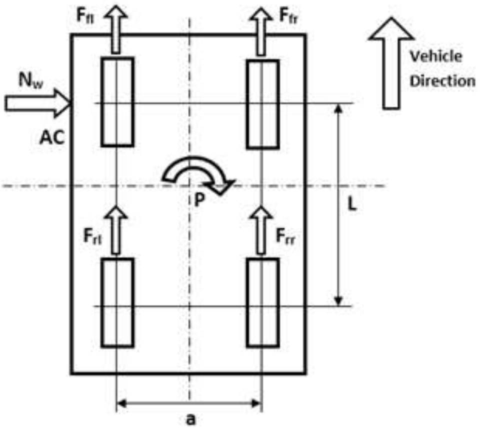

Fig. 9. Steady State Condition of a Vehicle travelling in a straight line

$$(F_{fl} + F_{rl})\, a/2 = (F_{fr} + F_{rr})\, a/2 \tag{14}$$

When a lateral disturbance acts on the vehicle, the moment on one side becomes greater than the other side, causing the vehicle to turn towards one direction. This is shown in Equation 15.

$$N_w + (F_{fl} + F_{rl})\, a/2 > (F_{fr} + F_{rr})\, a/2 \tag{15}$$

By varying the tractive effort available at each wheel, both sides of the Equation 15 can be made equal and the vehicle will travel in a straight path.

The yaw rate sensor provides the data in the form of rate of change of yaw angle i.e. angular velocity. The crosswind moment is calculated with the help of the data from the yaw sensor. With this value, the tractive effort required at each wheels can be determined. The Control Unit sends these signals to the Active Differential which distributes different torque to different wheels.

A steering wheel position sensor is used to determine whether the yaw created in the vehicle is due to the crosswinds or during cornering of the vehicle. This prevents the stability system from interrupting during unwanted situations.

The Simulink model of the Stability System is modelled and simulated. The system determines the tractive effort required at each wheels. In order to evaluate the system, the resulting moment is fed as an input to the vehicle motion and the vehicle behaviour is obtained. This facilitates easy comparison of the vehicle behaviour with and without the system.

In order to account for the delay in the system, a delay block was incorporated for the purpose of illustration. This makes the system vaguely realistic.

VI. RESULTS AND DISCUSSION

The results of Yaw displacement and Yaw rate with the Stability System were multi-plotted with the results of Yaw displacement and Yaw rate that were obtained without the Stability system. The comparison between the Yaw displacement with and without the Stability system is shown in Fig. 10.

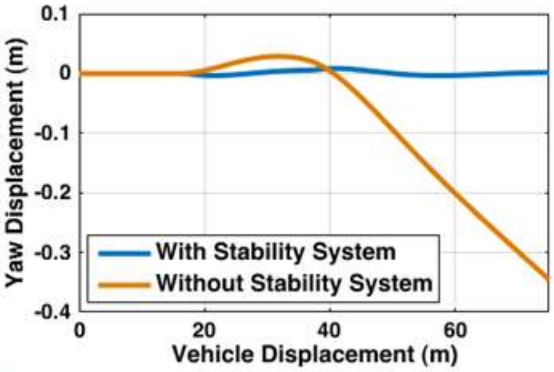

Fig. 10. Comparison of Yaw displacement of a Vehicle with and without the Stability

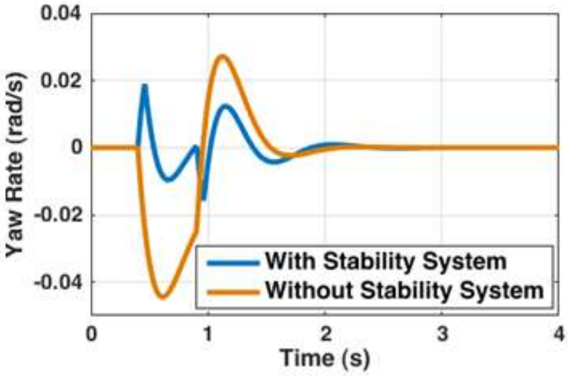

Fig. 11. Comparison of Yaw Rate of a Vehicle with and without the Stability

A noticeable difference has been obtained. The vehicle without the system kept deviating while the vehicle with the system followed the intended path with little deviation.

The comparison of the Yaw rate in vehicles with and without the Stability system is shown in Fig. 11. A significant difference is also found in the Yaw rate.

It can be thus proved by simulation that the Stability System, which increases the crosswind stability of a vehicle has been successfully modelled, simulated and evaluated. The system can further be made accurate by implementing delay in the sensors and actuators. The system makes use of the existing sensors in the vehicle which makes the implementation of the system simpler.

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